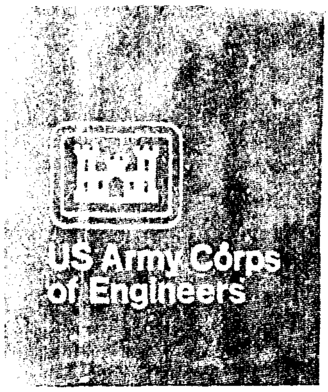

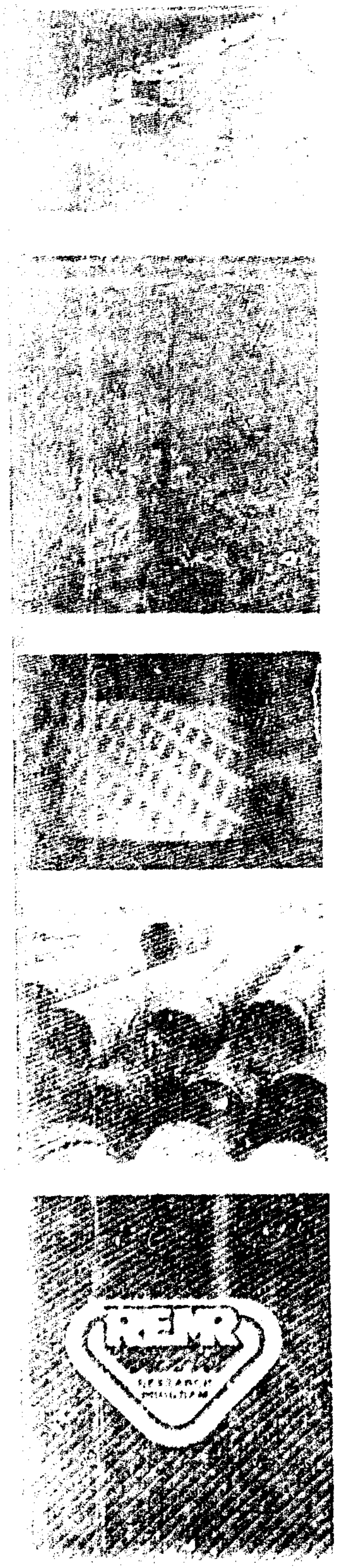

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

PROCEEDINGS OF REMR WORKSHOP ON RESEARCH PRIORITIES FOR DRAINAGE SYSTEM AND RELIEF WELL PROBLEMS

by

R. E. Leach, H. M. Taylor, Jr.

Geotechnical Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
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Final Report

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The following two letters used as part of the number designating technical reports of research published under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program identify the problem area under which the report was prepared:

	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS:

TOP — Flowing relief well at a levee toe.

SECOND — Piezometer flowing water.

THIRD — Clean wire wrapped well screen viewed in place with underwater camera.

BOTTOM — Old 24-in. bituminous-coated corrugated metal pipe removed from dam toe due to incrustation.

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PREFACE

The Proceedings of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program Workshop, "Research Priorities for Drainage System and Relief Well Problems," were prepared for the US Army Corps of Engineers (USACE), by the US Army Engineer Waterways Experiment Station (WES) under Civil Works Units 32312 and 32313. They provide a record of the presentations and the discusions that followed.

As part of the REMR Research Program, WES has been assigned two work units: (a) Restoration of Drainage System and (b) Restoration of Relief Wells. The objectives of these work units are to develop more efficient and economical methods for repair, evaluation, maintenance, and rehabilitation of drainage systems and relief wells. In initiating these work units, a workshop was held at the Holiday Inn-East in Denver, Colorado.

The workshop was hosted by WES under the direction of Mr. William F. McCleese, REMR Program Manager, Concrete Technology, Structures Laboratory, WES; and Mr. Jesse A. Pfeiffer, DRD Coordinator, USACE. The workshop was under the immediate direction of Messrs. Hugh M. Taylor, Jr. and Roy E. Leach, Principal Investigators, Soil Mechanics Division (SMD), Geotechnical Laboratory (GL), WES. Messrs. Taylor and Leach were responsible for organizing the workshop and making all arrangements. Mr. Arthur H. Walz was the USACE Technical Monitor. Ms. Ruth Lipscomb, WES, assisted in the arrangements for the workshop and for taking notes from which the Proceedings were prepared. General supervision was provided by Mr. Clifford L. McAnear, Chief, SMD, and Dr. William F. Marcuson III, Chief, GL.

Acting Commander and Director of WES during the preparation and publication of this report was LTC Jack R. Stephens, EN. Technical Director was Dr. Robert W. Whalin.

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16. SUPPLEMENTARY NOTATION
See reverse

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*

Drainage	Maintenance	Repair	Workshop
Drains	Rehabilitation	Research	
Evaluation	Relief wells	Subsurface	

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

At a Corps of Engineers workshop on 16-17 April 1985, research needs for restoration of drainage systems and relief wells for earth and earth supported structures were discussed and prioritized. Proceedings of the workshop are summarized. The primary purpose of the workshop was to identify problems and obtain field input to the direction of future research.

The presentations and resulting discussions produced the following proposed research areas in descending order of priority:

(Continued)

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16. SUPPLEMENTARY NOTATION (Continued).

A report of the Geotechnical problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. This report is available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

19. ABSTRACT (Continued).

a. Drainage systems:
   (1) Evaluation and rehabilitation of deep horizontal and vertical drains.
   (2) Geotextile guidance for drains.
   (3) New products information; technology transfer.
   (4) Evaluation of subsurface problems.

b. Relief wells:
   (1) Maintenance procedures and use of chemicals.
   (2) Inspection and evaluation methods.
   (3) Other more specific items.
      (a) Iron bacteria.
      (b) Check and flap valves.
      (c) Wood stave replacements.
      (d) Small flow meters
      (e) Exploration techniques.
      (f) Vandalism.

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
gallons (US liquid)	3.785412	cubic decimetres
inches	2.54	centimetres
pounds (force) per square inch	6.894757	kilopascals
pounds (force)	4.448222	newtons
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre

PROCEEDINGS OF REMR WORKSHOP ON RESEARCH PRIORITIES FOR DRAINAGE SYSTEM AND RELIEF WELL PROBLEMS

INTRODUCTION

1. The Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Workshop on drainage system and relief well problems was held in Denver, Colorado, on 16-17 April 1985. The workshop was sponsored jointly by REMR Work Unit 32312, "Restoration of Drainage Systems," and Work Unit 32313, "Restoration of Relief Wells." Because of the similarity of problems under the two work units, a joint workshop was considered desirable.

2. The objectives of the workshop were as follows:

   a. Acquaint Corps of Engineer (CE) personnel with the purposes of the research work units.

   b. Identify problems related to the operation and maintenance of drainage systems and relief wells.

   c. Identify potential solutions to the problem areas and obtain field input to the direction of future research.

3. The workshop was attended by 36 people from the Corps of Engineer Districts, Bureau of Reclamation, and several private organizations. A list of attendees is given on the following page. Informal presentations were made on the drainage and relief well systems in the CE Districts. At the conclusion of the presentations, the District personnel were asked to comment on problem areas that needed research including priorities.

ATTENDEES

REMR Workshop on Drainage System and Relief Well Problems

Denver, Colorado 16-17 April 1985

Name	Organization
Albritton, John	MRD
Canning, Charles	ORD
Chisolm, Ed	LMK
Christopher, Jack	USBR
Edris, Earl	WES
Ellington, Al	NCS
Farmer, Ron	SPN
Frank, Larry	ORH
Gatz, Joe	WES
Gerry, Easley	WES
Hackett, Glen	NWWA*
Jenkins, John	NPD
Karns, Dennis	MRK
Lauro, Larry	SPD
Lavery, Patty	WES
Leach, Roy	WES
Lipscomb, Ruthie	WES
McDaniel, Tomiann	MRO
Miller, Paul	WES
Monroe, John	LMM
Monzingo, Jack	MRO
Moore, Bruce	LMS
Moylan, John	MRK
Napolitano, Phil	LMN
Parrillo, Dan	SPD
Pendrell, Doug	MRO
Plummer, Tom	ORH
Sayles, Frank	CRREL

(Continued)

* National Water Well Association.

List of Attendees Concluded

Name	Organization
Sherman, Walter C.	Tulane University
Simmons, Marvin	ORN
Smith, Fred	LMN
Taylor, Hugh	WES
Walz, Art	OCE
Wilkinson, Tom	NCB
Wise, John	SWF
Zaidi, Sibte	NCR

AGENDA

REMR Workshop for Drainage System and Relief Well Problems

16-17 April 1985

Denver, Colorado

Tuesday - 16 April 1985	Presentations	Speakers
8:00 - 8:20	Registration	
8.20 - 8:45	REMR Overview	Art Walz, OCE
8:45 - 8:55	REMR Work Unit, Restoration of Drainage Systems	Hugh Taylor, WES
8:55 - 9:05	REMR Work Unit, Restoration of Relief Wells	Roy Leach, WES
9:05 - 9:35	Break	
9:35 - 9:45	Announcements, Handouts, Priorities	
9:45 - 10:25	Relief Wells and Drainage Systems in Memphis District	John Moore, LMM
10:25 - 11:05	Performance of Underdrainage Systems in St. Louis District	Bruce Moore, LMS
11:05 - 11:30	Discussion	
11:30 - 1:00	Lunch	
1:00 - 1:40	Problems Experienced and Remedial Measures Used in Vicksburg District	Ed Chisolm, LMK
1:40 - 2:05	Vertical Drain Installation at Kanapolis Dam	Dennis Karns, MRK
2:05 - 2:25	Discussion	
2:25 - 2:55	Break	
2:55 - 3:30	Relief Well Rehabilitation Techniques	John Moylan, MRK
3:30 - 3:50	Problems Encountered in Relief Well Rehabilitation	Tomiann McDaniel, MRO
3:50 - 4:00	Discussion	

(Continued)

AGENDA (Concluded)

Wednesday - 17 April 1985	Presentations	Speakers
8:00 - 8:25	Drainage Behind Eisenhower and Snell Locks in St Lawrence Seaway	Tom Wilkinson, NCB
8:25 - 8:35	Problems and Possible Solutions in North Pacific Division	John Jenkins, NPD
8:35 - 8:45	Problems in Huntington District	Larry Franks, ORH
8:45 - 9:00	Discussion	
9:00 - 9:25	Drainage Systems in Nashville District	Marvin Simmons, ORN
9:25 - 9:35	Discussion	
9:35 - 11:10	Iron Bacteria Occurrence, Problems and Control Methods in Water Wells	Glenn Hackett, NWWA
11:10 - 11:40	Rehabilitation of Relief Well Systems at Lavon Lake, Texas	John Wise, SWF
11:40 - 12:00	Discussion	
12:00 - 1:30	Lunch	
1:30 - 2:10	Innovative Methods for REMR Systems	Walter C. Sherman, Jr. Tulane University
2:10 - 2:30	Data Base Applications for REMR Drainage System Problems	Earl Edris, WES
2:30 - 3:00	Old River Overbank Structure Relief Well Rehabilitation	Joe Gatz, WES
3:00 - 3:30	Break	
3:30 - 4:00	Summary of Problems/ Priorities	Hugh Taylor, WES Roy Leach, WES
4:00	Adjourn	

REMR OVERVIEW

Art Walz
OFFICE CHIEF OF ENGINEERS

1. In the past the Corps of Engineers has held workshops devoted primarily to design and construction of new hydraulic structures for water resource development, but as these structures have aged the scope of the workshops have shifted to upkeep or maintenance. From discussion at these workshops, it was concluded that repair, evaluation, maintenance, and rehabilitation (REMR) type problems could not be solved with existing technology, therefore, now we see more workshops related specifically to REMR problems. The development of the REMR research program is documented in the "REMR RESEARCH PROGRAM DEVELOPMENT REPORT" completed in February 1983, and it covers the areas of: Concrete and Steel Structures, Geotechnical, Hydraulics, Coastal, Electrical and Mechanical, Environmental Impact, and Operations Management. Two of the problem areas "Restoration of Drainage Systems" and "Restoration of Relief Wells" are the subject of this workshop.

2. Seepage control if needed is a critical safety feature that has to perform as designed to insure a safe, reliable structure. With seepage control as only one item under the Operations and Maintenance budget, money and manpower do not seem to stretch far enough to keep top notch maintenance programs in place. Often it turns out to be "emergency management" money that is used to rehabilitate drains, underdrains, and relief wells after excess pressures develop or some type of distress is noted. The REMR program was set up to provide help by determining cost reductions in maintenance procedures, by locating replacement materials, and by determining check procedures whereby maintenance time schedules may be extended.

REMR WORK UNIT - RESTORATION OF DRAINAGE SYSTEMS

Hugh Taylor, Jr.
US Army Engineer Waterways Experiment Station

1. A significant number of dams throughout the United States were built without benefit of modern technology. By prolonging the active life of a dam, we preserve the value of a vital facility.

2. Seepage of varying degrees occur on all projects. Evaluating the seriousness of a seepage problem and then the effectiveness of a repair, replacement, or alternative relief systems are the major problems requiring attention in drainage systems.

3. The objective in restoration of drainage systems is to develop procedures and methods for improving, redeveloping and maintaining the flow in deteriorated critical drainage systems of earth and earth supported structures.

4. Accomplishments to date include identifying the following problems from REMR trip reports and from discussions with several Corps Divisions and Districts:

- a. Backflooding of wing wall backfill drainage and collector systems due to malfunctioning check valves (same valve used on relief wells).
- b. Encrustation of drainage systems, i.e., gallery drains.
- c. Siltation and clogging of underslab drainage.
- d. Monitoring and evaluating problems and repairs.

Similar problems have been discussed with other government agencies, architect-engineers and several University staff and research groups such as:

- a. Soil Conservation Service.
- b. Tennessee Valley Authority.
- c. Bureau of Reclamation.
- d. Federal Highway Administration.
- e. Bureau of Mines.
- f. Minerals Management Agency.
- g. University of Florida.
- h. Montana State University.
- i. Tulane University.

5. This workshop was planned to identify the Corps drainage and relief well problems, consider solutions and set priorities for direction of research in the Restoration of Drainage Systems and Restoration of Relief Wells Work Units.

REMR WORK UNIT-RESTORATION OF RELIEF WELLS

Roy Leach

US Army Engineer Waterways Experiment Station

1. CE levees and dams have thousands of relief wells installed to control uplift pressure near downstream toes and beneath stilling basins. Maintenance and rehabilitation constitute a major effort due to vandalism and deterioration of more recent manufactured well screens and of older wooden stave screens. A study of soil and water chemistry along with flow characteristics determines factors which contribute to actual deterioration of screen material or the clogging of the screen, filters, and the surrounding material. The state-of-the-art for non production water wells has not developed sufficiently to provide less costly more durable screen replacement materials, or cost efficient well rejuvenation methods.

2. The initial documentation for this work unit and REMR trip reports by the principle investigators identified certain groups of problems or complaints. In general the complaints were an outgrowth of economic considerations with the following listed most often: (a) reliability of check valves, (b) durability of screens and guards, (c) excessive maintenance, (d) methods to increase effectiveness, and (e) methods to reduce costs. For these complaints the following problems were documented for cases where the mode of failure or need for restoration could be identified and categorized according to source: (a) corrosion, (b) incrustation, (c) deterioration (wood staves), (d) vandalism, and (e) siltation.

3. A literature search to determine available methods of rehabilitation was conducted including both industry and CE sources. The following are more or less standard methods found in practice and someone in the CE has used each or a combination in well rehabilitation work: (a) pumping, (b) surging, (c) jetting, (d) acidizing, (e) chlorination, and (f) other chemical stimulation. Alternate methods found in the literature that have had differing amounts of success are: (a) lime applications at the surface, (b) the Vyredox method - forcing oxygen-rich water into an acquifer away from the well as a growth medium interceptor for bacteria that normally are attracted to the well (see Appendix A), (c) activated carbon filters in the well, (d) steam cleaning or pasteurization, and (e) ultra-sonic scrubbers. Other methods were found

but they appeared to be unsuited or too expensive for water producing wells, especially non-production wells.

4. From the literature search and CE contacts it appears that initial research should cover such areas as: (a) water chemistry and its relation to incrustation and biological growth, (b) influence of seepage or flow rate on incrustation, (c) geologic and hydrologic factors, and (d) construction and rehabilitation methods. The present goals for this study are to use the results to prepare documentation outlining methods for determining the need for rehabilitation and optimum rehabilitation procedures.

RELIEF WELLS AND DRAINAGE SYSTEMS IN MEMPHIS DISTRICT

John Monroe
US Army Corps of Engineers
Memphis District

1. The Memphis District has installed approximately 110 relief wells primarily along levees below Cape Girardeau, Missouri. Although there is no formal maintenance program, the wells are closely monitored. Difficulties have been experienced with the well outlets, three breaks in the galvanized corrugated pipe occurring in one year. The protective metal well guards shown in Figure 1 have recently been replaced by an improved type proposed by Johnson Screens Division, UOP, Inc. The new well guard shown in Figure 2 consists of a section of 20-in. diameter Johnson stainless steel well screen. The new well guard is considered more efficient, less corrosive, and costs only 3 percent more than the old style.

2. The relief wells on the riverside of the St. Johns Bayou Drainage Structure are not functioning properly. The well outlets were protected by flap gates that would not seal properly. They were replaced after 8 years. The wells are probably filled with silt. The stilling basin has shown no signs of distress; however deep pressure relief is needed. The net uplifts, as measured by three piezometers, amounts to 3- to 4-1/2 ft. It may be more economical to replace the stilling basin with an anchored slab than to install additional wells.

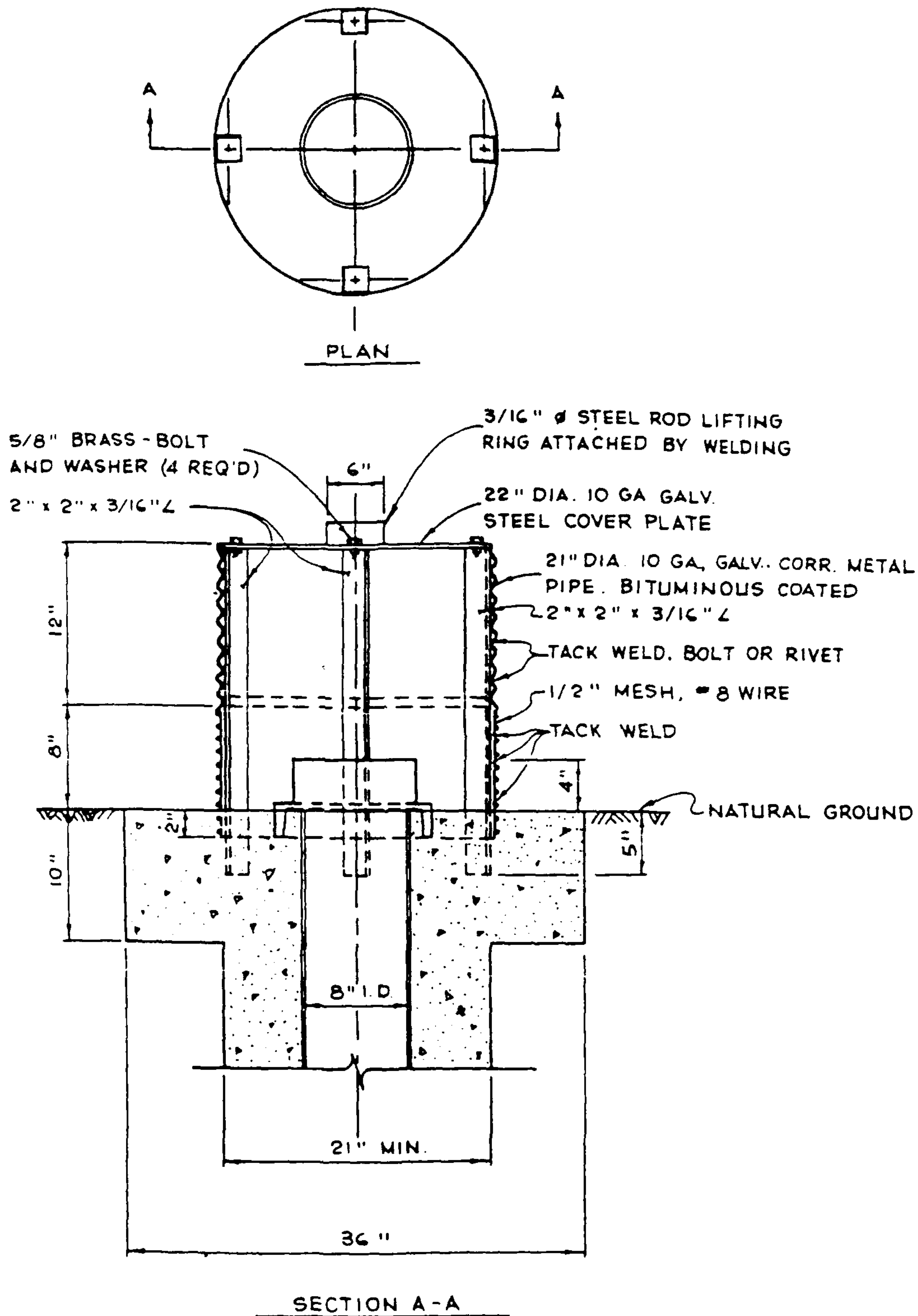

Figure 1. Metal well guard detail

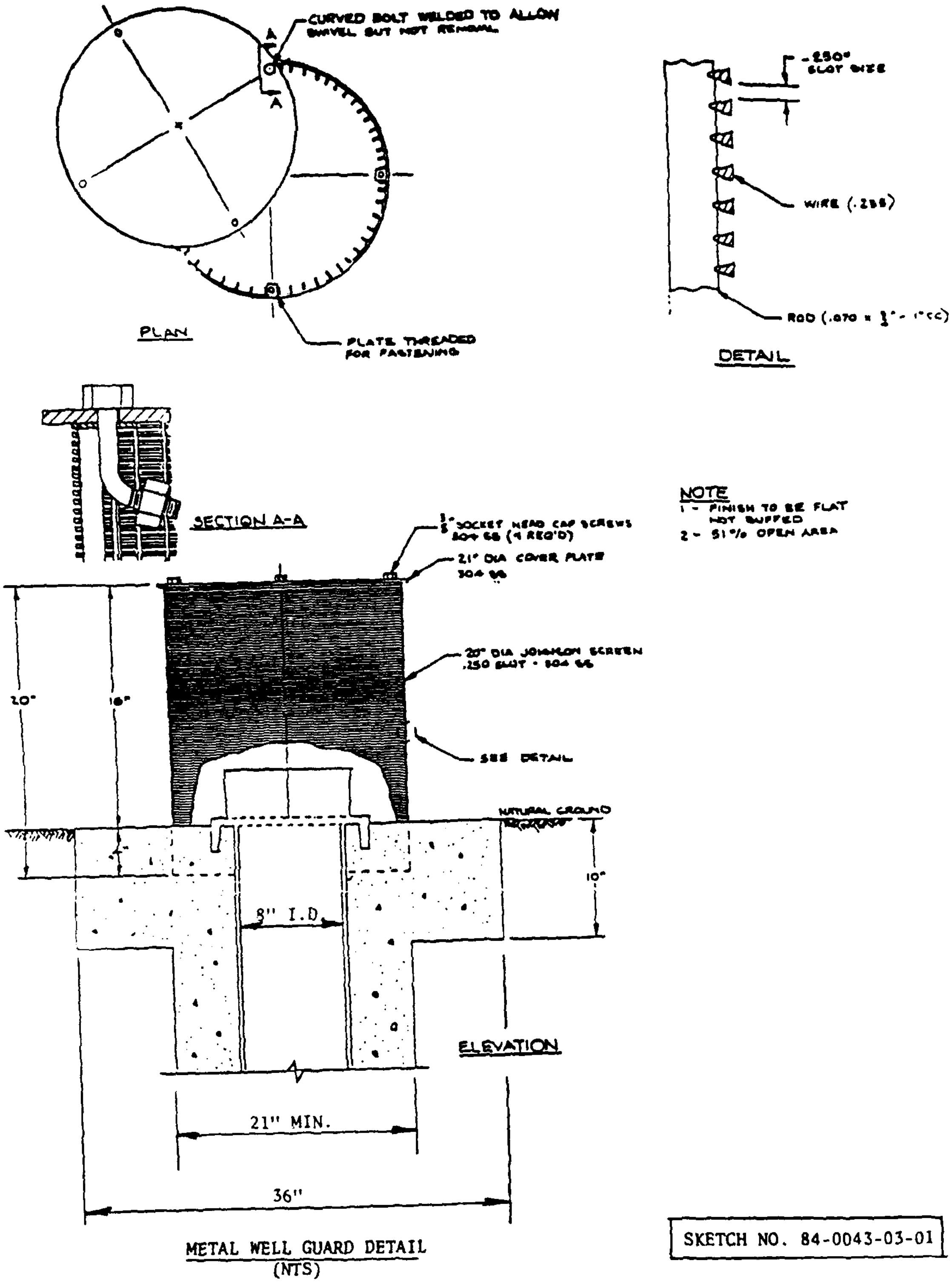

Figure 2. New wellguard

PERFORMANCE OF UNDERDRAINAGE SYSTEMS IN ST. LOUIS DISTRICT

Bruce Moore
US Army Corps of Engineers
St. Louis District

1. A system of over 2,000 relief wells was installed along the main-line levees in the upper Mississippi Valley to provide seepage control during high water. The wells were installed during the period 1953 to 1955 and maintained during the period 1960 to 1973. Losses in well efficiency were attributed to iron infestation. Maintenance in urban areas was generally unsatisfactory. Difficulties were encountered in farming areas where farmers complained of the increased seepage flows and sometimes blocked the wells with sandbags. With the introduction of temporary standpipes and a vigorous public relations campaign, the farmers were induced to accept the relief wells as an effective means of stopping sand boils. Although the wells were subjected to a gradual loss in efficiency as indicated by periodic pumping tests, observations during the 1973 high water indicated a regeneration with the wells restored to their original efficiency.

2. In an area in East St. Louis (Chain of Rock Reach) which is covered by a thin blanket of sand, flow from the relief wells is handled by a porous concrete ditch. The porous concrete was constructed of step-graded aggregate about 4 in. thick. It has not shown any signs of deterioration over the last 25 years. A similar drain constructed at present would probably incorporate a filter fabric.

3. The rapid deterioration of dewatering wells at the Kaskaskia Lock and Dam Project was attributed to calcium chloride. The contractor stored the calcium chloride mix in ponds before using it to retard concrete set time. Leakage from the ponds migrated to the well systems depositing incrustants on the screens.

4. The St. Louis District started using plastic, including fiberglass, well screens about 10 years ago. A major problem with introducing new drainage materials is the long period required before they are accepted by the Corps of Engineers. Much time is required to research, test, and evaluate experience. This work should be centralized for the benefit of the Districts.

5. Consideration should be given to cutoffs instead of drains where possible, using innovative techniques such as jet grouting.

6. The recent (1979) failure of a levee along the Illinois River was due to seepage. The levee built during the twenties using "stump yardage" (any material left after logging) construction had become completely saturated at the time of failure.

7. At the conclusion of Mr. Moore's speech, a brief discussion was held. The effectiveness of horizontal drains for embankments of fat clays or shales was brought out by several discussers. At Grenada Dam, continuous wire wound PVC screens were installed 4 years ago to remove through seepage collected in the horizontal drainage blanket. Although, the screens extend only about 10 ft into the drainage blanket, they have been effective in "drying" the toe of the dam.

8. Several discussers commented on the preferred type of protective covers for well outlets. Concrete boxes were recommended by Mr. Walz. Mr. Chisolm commented on the effectiveness of the football shaped well outlets in the drainage ditches used at Sardis Dam. The closed upstream end forced flow to bypass the outlet while the open downstream end allowed the well overflow to enter the drainage ditch. Wooden boxes were noted to be safer against vandalism, while corrugated bituminous coated steel pipe was also considered a desirable alternative.

PROBLEMS EXPERIENCED AND REMEDIAL MEASURES
USED IN VICKSBURG DISTRICT

Edward Chisolm
US Army Corps of Engineers
Vicksburg District

1. Underseepage control at Grenada Dam, completed in 1954, was originally provided by a line of relief wells discharging into a buried corrugated metal pipe along the downstream toe. Soon after the dam was placed in operation, sinks appeared over the collector pipe, and it was found that fine material was piping into the pipe through joint openings and bolt holes. Major repairs were necessary; it eventually became necessary to replace the collector pipe with a paved open channel.

2. At Sardis Dam, underseepage control was provided by a system of eighty-two 6-in.-diam wooden stave relief wells installed along the toe of the dam in 1946. Gradually, the wells became less efficient, and in the 1960's it was necessary to abandon some of the wells and to install some additional wells. The loss in efficiency was attributed to iron bacteria. In 1977, the entire system of 109 wells was replaced by a system of new wells incorporating Johnson stainless steel well screens. In order to maintain the efficiency of the wells they are pump tested and treated every 5 years with chlorine and chemical solutions (HTH and trisodium phosphates). Jetting with horizontal jets at 140 psi has been used, but it is not effective in removing iron deposits from the gravel pack. Maintenance costs average about $50,000 every 5 years. The flat type check valves installed on the new wells have not been entirely satisfactory, and improvements would be beneficial.

3. Problems have developed at Grenada Dam where severe erosion of embankment soils along the toe drainage system has occurred. The erosion is attributed to the dispersive nature of the embankment materials.

4. A general problem associated with V-shaped concrete drainage ditches has been the washing out of soil beneath the ditches and development of uplift pressures causing movement and cracking. The problem is attributed to the breakdown of the filter material, especially that which was installed 20 to 30 years ago. Research on filter requirements beneath ditch linings would be beneficial.

5. There are various methods for cleaning wall drainage systems. At Enid Dam, a high-pressure sewer cleaning device was employed to flush the collector pipes. Flushing high volumes of water through the collector pipes past movable plugs designed to force water through the perforations in the collector pipes was effective at Grenada Dam.

6. Regarding details of the chemical treatment of wells in the Vicksburg District, the general procedures recommended by the Johnson Division, UOP, Inc. book, "Ground Water and Wells," were used with adjustments made according to experience.

VERTICAL DRAIN INSTALLATION AT KANAPOLIS DAM

Dennis Karns
US Army Corps of Engineers
Kansas City District

1. Seepage emerging on the downstream slope of Kanapolis Dam was attributed to the presence of pervious lenses or cracks within the impervious zone. The presence of a horizontal drainage blanket was thus not effective in intercepting the through seepage. In order to intercept the seepage it was decided to install vertical sand drains downstream of the impervious zone to intersect the horizontal drainage blanket. The 10-in.-diam drains were spaced at 10 to 20 ft with a maximum depth of 70 ft. Construction procedures were a major concern, and a field test program was therefore conducted. The filter sand initially selected was found to be too fine, and a coarser material was used. After much experimentation, a procedure was developed using a hollow stem auger as a tremie. The sand was washed in place, and the auger pulled while being simultaneously vibrated. Densities were checked by means of a cone penetrometer. Because of concerns that clogging would occur in the random zones, a special filter cloth sock was devised to enclose the sand drains for their fill depth. The drains were installed at the rate of two and a half drains per day at a cost of approximately $1,000 per day.

2. After a brief discussion regarding the decision to use drains rather than an impervious cutoff, it was concluded that the drains were more economical. A similar sand injection method being employed at Waterbury dam was discussed.

RELIEF WELL REHABILITATION TECHNIQUES

John Moylan
US Army Corps of Engineers
Kansas City District

1. Relief wells in the Kansas City District consist mostly of wooden screens and risers and flow most of the time. The wooden screens are considered very fragile because jetting, and the use of surge blocks if done too vigorously can do serious damage to the screens. The effects of chlorine treatment on the wood is a matter of concern. Data are being collected on the chemistry of the well water. Questions arise concerning gravel pack and slot size criteria for new wells, as Corps criteria[1] differ from those used by the well industry[2].

2. Rehabilitation efforts on existing wells are conducted every 5 years and usually consist of the following steps:

- a. Record elevation of water in test well, adjacent wells, and piezometers.
- b. Measure flow in well using a flow meter.
- c. Determine bottom elevation of well, then bail if more than 6-in. of sand present.
- d. Surge well with bailer until no further material enters well.
- e. Read all piezometers.
- f. Add chlorine (200-500 ppm, more if iron is present) and polyphosphates; disinfect drilling tools.
- g. Mix chemical in well with bailer for 4 hours.
- h. Allow to set overnight.
- i. Repeat surging and bailing (optional).
- j. Measure well flow and read all piezometers.

3. As far as new wells are concerned, there are advantages to using stainless steel well screens. The advantages include long life, resistance to corrosion, and greater open area in the screen.

4. Whether chlorine treatment will have a deleterious effect on wood screen is a matter of uncertainty and research should be conducted to provide

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1 EM 1110-2-1913, 31 March 1978, Design and Construction of Levees, US Army Corps of Engineers.

2 Ground Water and Wells, seventh printing 1982, Johnson Division, UOP, Inc.

answers. In the discussion that followed, Mr. Pendrell mentioned problems with long (650-900 ft) horizontal PVC drains in shales. The drains installed in the late 1970's were initially successful in reducing piezometric levels but subsequently became less effective. A stiff brush has been effective on shorter drains, but there is concern about using the stiff brush on longer drains because of scratching the PVC liners. Experience on cleaning long horizontal drains appears to be lacking.

PROBLEMS ENCOUNTERED IN RELIEF WELL REHABILITATION

Tomiann McDaniel
US Army Corps of Engineers
Omaha District

1. Relief wells in the Omaha District consist primarily of wooden screens and riser pipes, and the problems are similar to those described by others. Many wells have been functioning satisfactorily but will need rehabilitation soon. On some wells, the riser and screen section are out of alignment, and the gravel pack has settled. Kinks in the well screens have been noted. Alignment problems cause difficulty in using mechanical action for rehabilitation. Some wells were jetted, and sulfamic acid was added and allowed to stand for 24 hr before removal. The flows were difficult to impossible to measure due to relief well pit designs. Down well flow meters have been used to evaluate the effectiveness of rehabilitation efforts on flowing wells in some cases. A borehole TV camera was used that indicated offsets at joints and much incrustation in the screen openings. Consideration is being given to replacing the wells instead of further rehabilitation efforts.

2. In regard to a question concerning check valves, it was stated that the wells were not equipped with check valves. Furthermore, some of the wells are subjected to frequent backflow.

3. Experience in or research involving other methods of rehabilitation such as use of high frequency sound waves would be of interest.

PROBLEMS AND POSSIBLE SOLUTIONS IN NORTH PACIFIC DIVISION

John Jenkins
US Army Corps of Engineers
North Pacific Division

1. In the North Pacific Division, foundation drain hole clean out has been established on a 5-year cycle. Each district sets up its own schedule; probably the major problem is maintaining the schedule. There are frequent delays for higher priority work. The usual methods of cleaning is with wire brush and pressure washing with redrilling as required.

2. At Chief Joseph Dam, the Seattle District has developed an effective cleaning method that uses a small air motor with hinged cutting arms. This device was designed and is marketed for cleaning boiler tubes. From the hole clean out, the motor is attached to a 3/4-in. pipe (10-ft lengths), which supplies air and serves as a handle. Water to wash out cuttings is supplied by a 5/8-in. hose. This method works well as long as the rock is fairly tight. Otherwise, the cutter arms will displace rock from the sides of the hole and cause blockages.

3. At Libby Dam, another simplifying procedure has been developed. As soon as a hole is clean, a 1-1/2-in. plastic pipe is inserted. The pipe column remains in the hole resting on the bottom and projecting above the collar. At the next clean out, the hole can be checked simply by attaching a water hose to the plastic pipe and applying water under pressure. Water return up the hole, outside the plastic pipe, indicated the openness of the hole. This method is much faster than inserting a hose and working it to the bottom. Raising and lowering the plastic pipe will dislodge minor blockages.

4. The use of high-pressure (25,000 to 50,000 psi), low-volume (8 to 10 gpm) washing methods has been considered. There were questions whether anyone else has had experience with this type of equipment. It would appear to have application in large concrete dams if the equipment will fit in the galleries. The high pressure (below the pressure that cuts concrete) would cut the calcareous material that forms on the sides of the hole.

5. The largest relief well installation in the division is at Moose Creek Dam just outside Fairbanks, AK. There we installed one hundred twenty-five 12-in. wells ranging in depth from 25 to 125 ft depending on the depth to

permafrost. They were all stainless steel continuous wrap wire screens with a steel pipe riser. There has not been a full test on this installation yet, but with a partial pool last year they appeared to work OK. The only major problem appears to be freezing, and personnel at the project are prepared to thaw them with a portable steam generator, if necessary. Moose Creek wells replace an embankment drainage system that did not work due to improper gradation and improper placement.

6. Relief wells have been installed in abutment drainage systems at Chief Joseph, Howard Hanson, and Fall Creek Dams. To date, they have not been a problem. At both Chief Joseph and Hanson Dams, the wells feed into drainage adits. At Hanson Dam risers extend to the surface, while at Chief Joseph the entire installation is generally below tail water.

7. The installation at Fall Creek replaces a failed drainage trench. The first attempt utilized sand backfilled auger borings. These were also unsuccessful. Then a 3-in. slotted PVC pipe was placed in 8-in. air-rotary boring with pea gravel backfill. A total of 96 wells were installed, grouted, and each connected to a 12-in. CMP header pipe. This installation has been in operation for 5 years and has been successful in reducing the uplift pressure. It appeared that the primary reason for failure of the first two systems was that they did not extend deep enough.

PROBLEMS IN HUNTINGTON DISTRICT

Larry Franks
US Army Corps of Engineers
Huntington District

1. The Huntington District has 14 project locations in West Virginia and Ohio with a total of 180 relief wells. The wells are located in widely varying foundation soils including silty sand alluvium and glacial outwash with open work gravel. Well screens are slotted galvanized steel, slotted fiberglass, or wire wound stainless steel. About two thirds of the wells normally do not flow except at high reservoir pools. The wells vary in depth between 110 and 150 ft.

2. The current monitoring program consists of well soundings, flow measurement, and reading piezometers on a yearly basis and after high pool levels. Well rehabilitation has a low priority because of funding limitations.

3. At Dillon Dam in South Central Ohio, there was a recent blockage of a drainage collector system as evidenced by water bubbling up through protective housing. New drainage ditches were installed. Subsequently, it was decided to rehabilitate the wells in order to restore their efficiency. The well screens consisting of slotted galvanized steel were treated with Calgon and soda ash. After surging the wells were pump tested. Lack of previous results prohibited an evaluation of the effectiveness of the procedure.

4. At the North Branch of Kokosing Dam, it was found that the galvanized steel well screens had deteriorated with sediments filling the well. Four of the wells were redrilled with new screens installed. In twelve of the wells stainless steel telescoping screens were inserted. All wells were surged and pumped tested after rehabilitation.

5. There is need for guidance on how best to contract for well rehabilitation. Information is needed on (a) determination of which wells need rehabilitation, (b) identification of the problem causing losses in well efficiency, and (c) methods to be used in well rehabilitation.

6. In the discussion of acid treatment of wells, Mr. Driscoll suggested that the acid should be left in the wells overnight but not longer.

DRAINAGE SYSTEMS IN NASHVILLE DISTRICT

Marvin Simmons
US Army Corps of Engineers
Nashville District

1. The divide cut on the Tennessee-Tombigbee Waterway is the only project in the Nashville District where relief wells have been employed. A total of 180 permanent relief wells were installed. The system includes deep wells on top of the cut to control artesian pressures and shallower wells on the slope extending almost to the base of the cut. The wells consist of 10-in.-diam PVC screens with 2-in. of gravel pack.

2. Iron bacteria were encountered in all wells and caused serious clogging of wells and pumps. Various disinfectants were tried with no success. In 1983, a sole source contract was let to a company reputed to have success with this type of problem. Five wells were treated at a cost of $50,000. The treatment, which included injection of chemicals at pressures of 8 psi, and jetting with air were not greatly successful. High pressures destroyed 1 well screen and the other wells continued to clog after treatment.

3. It appears that the stainless steel well screen originally proposed would have been preferable to the PVC screen, which is too delicate to withstand required cleaning. The well system has been turned over to the Mobile District for operation.

IRON BACTERIA OCCURRENCE, PROBLEMS AND CONTROL METHODS IN WATER WELLS

Glenn Hackett

National Water Well Association

1. The organization and activities of the National Water Well Association were described. Briefly, the association, which is headquartered in Worthington, Ohio, was founded in 1948 by Water Well Drillers and Suppliers. The association maintains an international library of groundwater technology, and their publications are for sale or loan to other libraries. They conduct seminars and symposia and undertake studies and research for many organizations.

2. A description of various types of iron bacteria, problems associated with their occurrence in groundwater and wells, and methods of control were included in the presentation. The lecture was based on a slide presentation available for rent from the National Water Well Association. The information presented is part of a report prepared by the NWWA under contract subsequent to the workshop and the full report is included as Appendix A.*

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* The report contained in Appendix A was prepared by the National Water Well Association under contract subsequent to the workshop.

REHABILITATION OF RELIEF WELL SYSTEM AT LAVON LAKE, TEXAS

John Wise
US Army Corps of Engineers
Fort Worth District

1. A system of 39 wells was installed along the toe of Lavon Lake Dam, Texas, to control underseepage after it was decided to raise the dam by 12 ft. The wells consisted of an 8-in.-diam slotted wood stave pipe pressure-treated with creosote and wrapped with filter cloth. The wells discharged into a corrugated aluminum collector pipe and were provided with aluminum check valves.

2. The drainage collector system and wells were plugged up within 5 years after they were installed. Material in the wells was a black tarlike substance that smelled like petroleum. There was no evidence of iron bacteria. The bottom part of the well screen appeared to have disappeared. The rubber gaskets on top of the well had completely disintegrated.

3. Remedial work was done under contract and included construction of a new collector system of 12-in. PVC pipe and rehabilitation of the wells. Each well was pumped initially at 5 gpm for 20 min before adding the chemicals, consisting of 15 lb of tri-sodium phosphate and 2 lb of calcium hypochlorite per 100 lb of water. The well was then surged for 15 min, airlifted at 30 psi for 1 hr, and left for 24 hr. The surging and flushing cycle was repeated two more times before running the final pumping test.

4. During the discussion, questions as to why filter cloth was used around the well screen did not provide a conclusive response. The black tarlike material was removed by pumping.

INNOVATIVE METHODS FOR REMR SYSTEMS

Walter C. Sherman, Jr.
Tulane University

1. Current methods for restoring relief wells and drains to their original efficiency were briefly summarized. The basic causes of reduced efficiency in well and drains are considered to be (a) mechanical clogging, (b) chemical incrustation, and (c) bacterial growth. Mechanical clogging is caused by the introduction of silt and clay particles into the wells or drains as a result of backflow. Chemical and physical methods employed for cleaning are only marginal effective, and the principal innovation appears to be an improved check valve to prevent backflow. Chemical incrustants, principally carbonates of calcium and magnesium, apparently can be treated with reasonable success with acid solutions.

2. Bacterial growth in the form of a gelatinous organic material (ochre) appears to be a major cause of well and drain plugging in CE installations. A large variety of chemicals and anti bacterial agents have been employed with mixed results. Furthermore, treatments that are successful frequently are limited to short durations. Physical methods of well treatment may offer the best innovative solution to this problem. These methods include (a) ultraviolet light, (b) ultrasonics, (c) elevation of water temperatures, (d) changing the redox potential (Vyredox method) (see Appendix A), and (e) cathodic protection. These methods have been investigated in limited laboratory and field applications and appear to offer potential for further field testing. Elevation of water temperatures to the pasteurization range presently appears to offer the most promise as an innovative method.

DATA BASE APPLICATIONS FOR REMR DRAINAGE SYSTEMS PROBLEMS

Earl Edris
US Army Corps of Engineers
Waterways Experiment Station

1. A computerized piezometer data package is available for monitoring and management of data for periodic inspection. It reduces raw data, flags questionable readings, and provides data plots. The data base package for the mainframe computer summarized below is documented in Instructional Report GL-85-2, "Piezometer Data Base Package: User's Guide", October 1985. The recommended microcomputer version of this package is documented in a draft instruction report, "Microcomputer Instrumentation Data Storage and Display Package; User's Guide".

2. Information stored included piezometer location, type and purpose of piezometer, reading dates and intervals, and other data associated with the observations such as pool and tailwater elevations, weir readings, precipitation, temperature etc. Definitions of table elements are given in Table 1. Examples of selected data elements are given in Table 2. Plotting capabilities include time-history plots, piezometer readings on cross sections, piezometer locations, and contours of selected water surfaces.

3. Plotting routines permit three separate vertical scales with up to three piezometers per scale. Special symbols are provided for piezometers that are dry, frozen or indicate zero readings. A bar chart for precipitation may also be included. In addition to cross-sectional plots, a grid map may also be generated and piezometric data contoured.

Table 1

Definition of Data Elements

Component Number	Element Abbreviation	Element Description	Key/Non-Key Designation	Type of Data	Field Size
C1	PROJ-NAME	Project-name	Key	Name	X(30)
C2	PROJ-RIVER	Project-river	Non-Key	Name	X(30)
C3	PROJ-STATE	Project-state	Non-Key	Name	X(5)
C4	PROJ-TOWN	Project-town	Non-Key	Name	X(20)
C5	DIST	District	Non-Key	Name	X(5)
C6	TYP-STRT	Type of structure	Non-Key	Name	X(20)
C7	CRT	Crest elevation	Non-Key	Dec	9999.9
C8	SPY	Spillway elevation	Non-Key	Dec	9999.9
C10	MXPL	Maximum pool elevation	Non-Key	Dec	9999.9
C11	MNPL	Minimum pool elevation	Non-Key	Dec	9999.9
C12	NRPL	Normal pool elevation	Non-Key	Dec	9999.9
C13	NXTW	Maximum tailwater elevation	Non-Key	Dec	9999.9
C14	MNTW	Minimum tailwater elevation	Non-Key	Dec	9999.9
C15	NRTW	Normal tailwater elevation	Non-Key	Dec	9999.9
C18	RECPL	Pool of record	Non-Key	Dec	9999.9
C19	DRPL	Date of record pool	Non-Key	Date	X(10)
C20	ALTPL	Alert pool	Non-Key	Dec	9999.9
C22	CONT-BEG	Date construction began	Non-Key	Date	X(10)
C24	CONT-COM	Date construction completed	Non-Key	Date	X(10)
C40	PIEZ	Repeating Group for Piezometers			
C41	PNO	Piezometer number	Key	Name	X(10)
C43	PFD	Feature description	Key	Name	X(10)
C45	PSTA	Station (dam station)	Key	Name	X(8)
C47	POFF	Offset (lock station)	Key	Name	X(8)
C49	TIPEL	Tip elevation	Key	Dec	9999.9
C51	TREL	Top of riser elevation	Key	Dec	9999.9
C53	PGS	Ground surface elevation	Key	Dec	9999.9
C55	RPD	Riser pipe diameter	Non-Key	Dec	9.999
C57	TPSL	Soil type at tip	Key	Name	X(7)
C59	TYPIEZ	Type of piezometer	Key	Name	X(20)

(Continued)

Table 1 (Concluded)

Component Number	Element Abbreviation	Element Description	Key/Non-Key Designation	Type of Data	Field Size
C61	PSAT	Status of piezometer	Key	Name	X(10)
C63	PDI	Date of installation	Key	Date	X(10)
C65	LOCINT	Location of installation report	Non-key	Name	X(10)
C67	PMIT	Method of installation	Non-key	Name	X(25)
C68	PIB	Installed by	Non-key	Name	X(15)
C69	PTEST	Method of testing piezometer	Non-key	Name	X(15)
C70	REFD	Reference drawing	Non-key	Name	X(20)
C71	CALB	Calibration constant	Non-key	Dec	99.99
C73	FLTMAT	Filter material	Non-key	Name	X(15)
C74	TPFLT	Top elevation of filter	Non-key	Dec	9999.9
C75	BTFLD	Bottom elevation of filter	Non-key	Dec	9999.9
C76	SALMAT	Seal material	Non-key	Name	X(15)
C77	TPSEAL	Top elevation of seal	Non-key	Dec	9999.9
C78	BTSEAL	Bottom elevation of seal	Non-key	Dec	9999.9
C81	PDTLR	Date last reading	Key	Date	X(10)
C82	PDTNR	Date next reading	Key	Date	X(10)
C83	PINT	Interval between readings	Key	Name	X(10)
C85	PTH1	1st Threshold value (reread piez)	Key	Dec	9999.9
C86	PTH2	2nd Threshold value (send warning to dist and project)	Key	Dec	9999.9
C87	PTH3	3rd Threshold value (reading above alert pool level)	Key	Dec	9999.9
C88					
	PTH4	4th Threshold value (reading above ground surface)	Key	Dec	9999.9
C90	PRED	Repeating Group for Piez Readings			
C91	PDTRD	Date of reading	Key	Date	X(10)
C93	PREAD	Reading (elevation)	Key	Dec	9999.9
C95	PMDRD	Method of obtaining reading	Key	Name	X(15)
C97	PRM	Remarks	Key	Name	X(20)

Table 2

Examples for Selected Data Elements

Component Number	Element Abbreviation	Description	Examples	Remarks
C1	PROJ-MANE	Project name	MICHAEL KIRWAN TIONESTA LAKE L&D No. 1 Red River	Any name up to 30 characters and spaces
C41	PNO	Piezometer number	70-C-1 78-T-1 POOL PRECIPITATION T.W. Weir	Any 10 character name for piezometer, water level, or weather readings
C45	PSTA	Station	100+00 200.50	Any 8 character name that will locate one coordinate of the instrument
C47	POFF	Offset	200 U/S 50 D/S 100.25	Any 8 character name that will locate other coordinate of the instrument
C49	TIPEL	Tip elevation	275.4	Elevation required for calculation of air actuated piezometer readings
C51	TREL	Top of riser elevation	301.5	Elevation required for calculation of open standpipe, uplift cell, gauge pressure, and staff readings
C55	RPD	Riser pipe diameter	1.375 1.25	Inside diameter of riser pipe expressed as a decimal
C59	TYPIEZ	Type of piezometer		Open standpipe pneumatic staff gauges types

(Continued)

Table 2 (Concluded)

Component Number	Element Abbreviation	Description	Examples	Remarks
				Sump Weir T.W. Pool Precip. A.T.
C71	CALB	Calibration constant	51.3	Used for 90° V-notch weir calculations
C81	PDTLR	Date last reading	12 May 1984	Any valid date. These must be updated by the user.
C82	PDTNR	Date next reading	12 June 1984	Any 10 character description
C83	PINT	Interval between readings	two months Next spring spring Next high water	40 days of the time between readings or when next reading should be
C95	PMDRD	Method of obtaining reading	Weighted line Electric probe TAPE Probe Gauge No. 2350	Any 15 character description of device used to make the reading

OLD RIVER OVERBANK STRUCTURE

Joe Gatz

US Army Corps of Engineers

Waterways Experiment Station

1. The Old River Overbank Structure, a flood control structure in the New Orleans District, is located on the west bank of the Mississippi River about 40 miles south of Natchez, Ms., and is founded on a relatively thin impervious top stratum underlain by highly permeable sand. The structure is slightly more than 0.6 miles in length and has 73 gate bays. Underseepage is controlled by 19 permanent pressure relief wells screened through about 60 percent of the substratum sand thickness. The wells are located through the stilling basin and discharge through the baffle blocks.

2. The wells are constructed of Douglas fir, wood stave screen and riser pipe. The screen slots are 1/8 in. wide vertical saw cuts. Well construction is typical of older relief wells throughout the lower Mississippi Valley. While the life expectancy of continuously submerged wood is long, rehabilitation is extremely difficult. These wells were installed by contract in 1957. Original pumping test data indicate specific capacities of the 19 wells ranged from 20-94 gpm per foot of drawdown and averaged 52. The wells were pump tested and rehabilitated by mechanical agitation using a surging block in 1966, 1970, and 1973 with only limited success. In the 1970 series, various detergents, water softeners, and cleaners were used with no apparent meaningful effect. The wells did not flow prior to the 1973 series of tests, they did flow later in 1973 and in 1982, 1983, and 1984.

3. Results of rehabilitation efforts of these wells through 1973 are depicted by a bar graph (Figure 1). Original specific capacity is shown in black, while the before and after specific capacity is shown by the hatched bars. The fact immediately obvious from this graph is drastically decreased effectiveness of these wells since installation. The bottom graph depicts specific capacity in percent of original. In 1970 the improvement in condition by the rehabilitation efforts was from 33 to 50 percent of original. In 1973 it was from 44 to 50 percent of original.

4. In addition to mechanical agitation in 1973, wells numbered 6, 8, 11, and 15 were treated with chemicals. Water and incrustation samples were

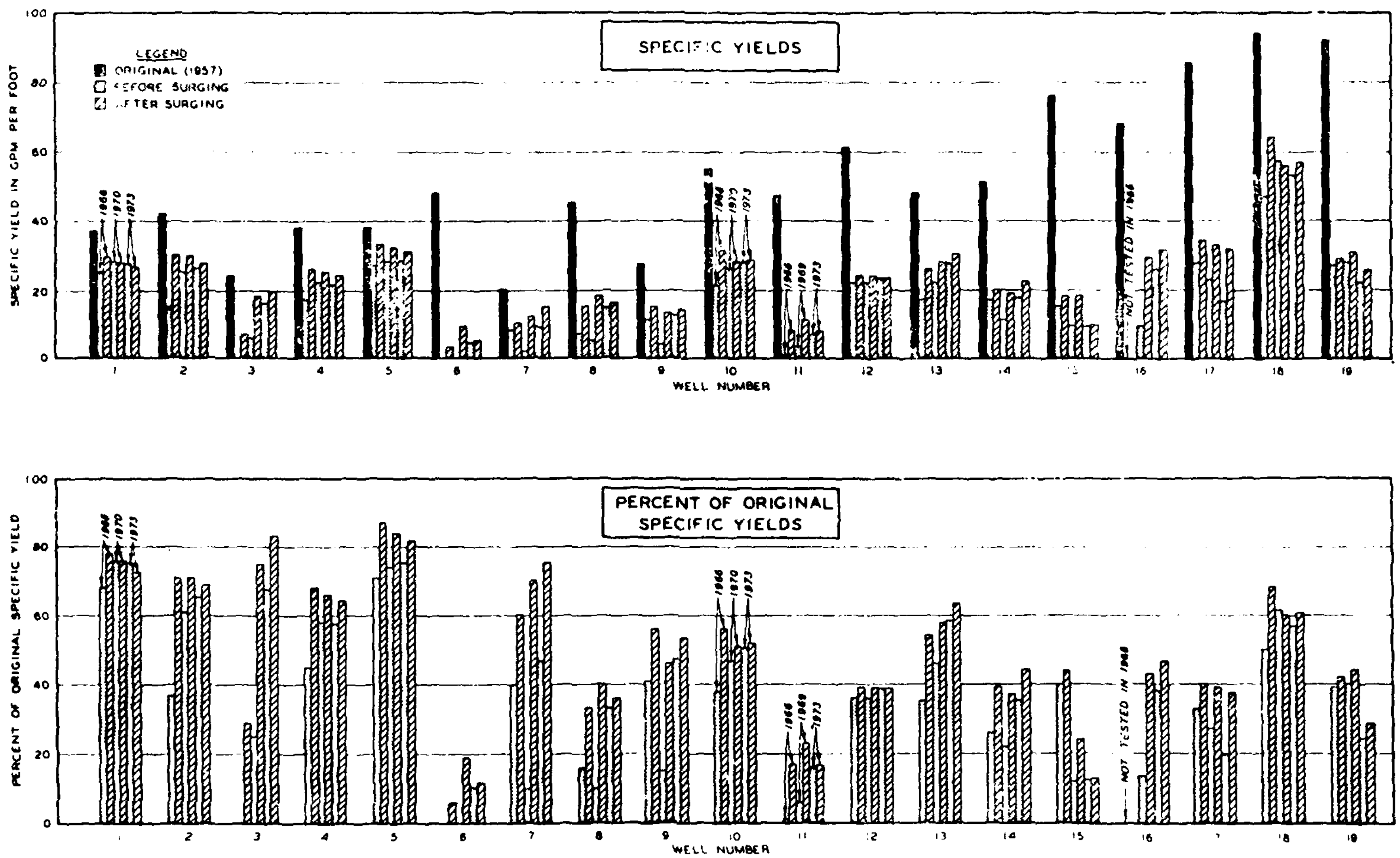

Figure 1. Specific capacity from rehabilitation efforts through 1973

collected from the four wells and analyzed. Calcium content in well 6 was high at 94 mg/ℓ and iron content in wells 8, 11, and 15 were extremely high, up to 96 mg/ℓ in well 11.

5. Chemical treatment of these wells was crude and consisted only in adding muratic acid to wells 6 and 15, Johnson's Nuwell to well 8, and Cotey Chemical Company's Dry Acid Special G to well 11. After injection of the acid materials, each well was surged to mix the acids in the well. After 24 hr the wells were again surged and pumped until a neutral pH value was attained in the effluent. Each well was treated with Welgicide and mixed by surging. After 24 hr the wells were again pump tested (Table 1). The treatments were apparently ineffective.

Table 1

Results of Pumping Tests on Wells Treated with Chemicals

		Specific Yield, gpm/ft Drawdown		
Well	Treating Agent	Original (1957)	Before Treatment (1973)	After Treatment (1973)
6	Muriatic acid	48.0	4.9	5.6
8	Nu-well	45.0	15.2	16.3
11	Dry acid special-G	47.0	7.5	7.9
15	Muriatic acid	76.0	9.4	9.7

6. In 1983-1984 the wells were again tested and rehabilitated by mechanical agitation. Water samples were collected and analyzed from wells 6 and 11 for comparison with data from samples 10 years previous. There was an obvious reversal in the chemical composition data. The iron content showed a marked reduction, one order of magnitude in well 6 and 2 orders of magnitude in well 11. These data approach that which should be expected from shallow wells and create some doubt as to the validity of the 1973 data. The indicated calcium content was reduced by 50 percent in well 6 and increased by 50 percent in well 11. An inspection of the wells with a borehole camera indicated no alarming structural damage from previous activities, including chemical treatments.

7. Increase in specific capacity from the 1983-1984 effort is certainly not impressive data (Figures 2 and 3). The after treatment average specific

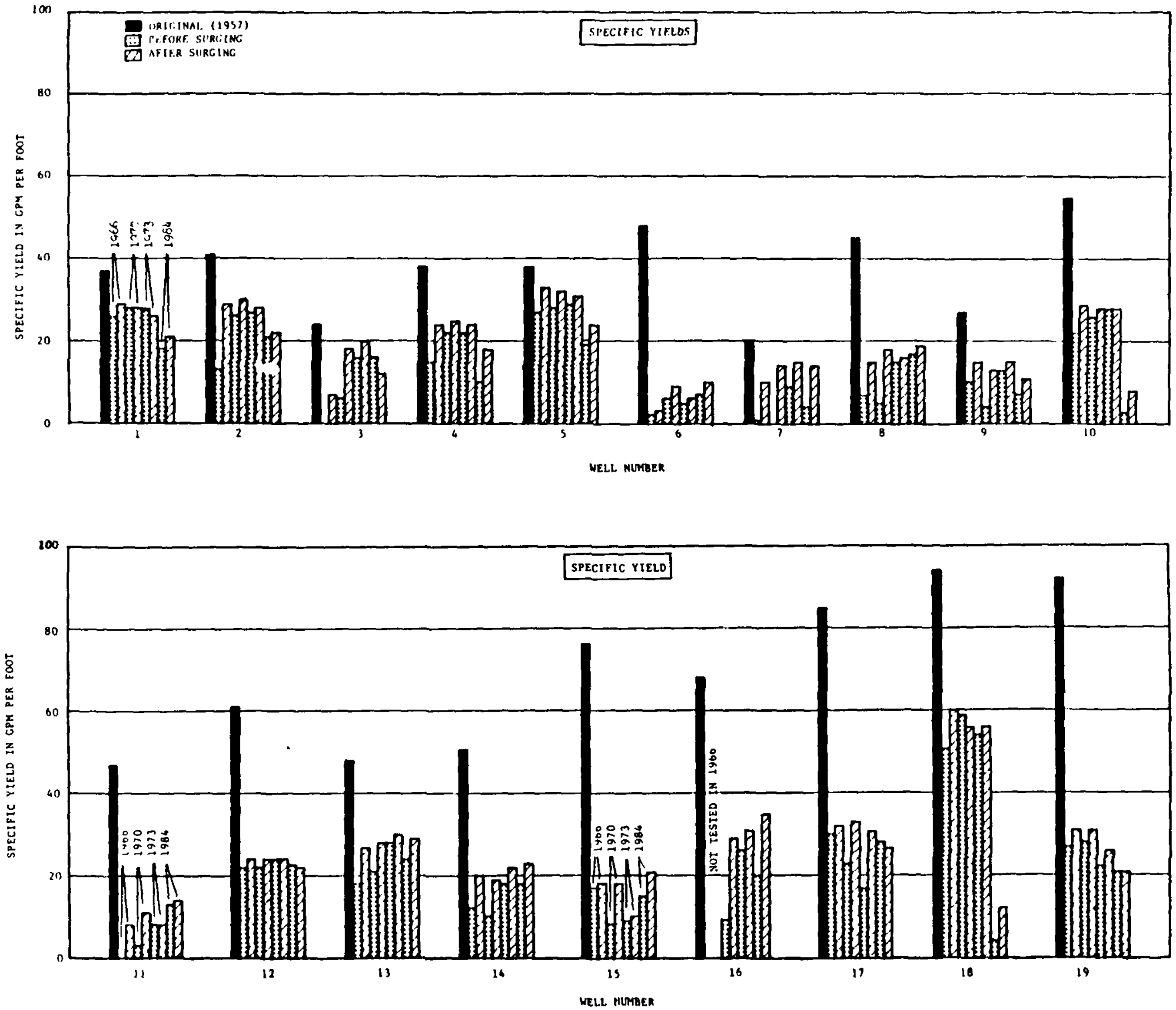

Figure 2. Specific capacity, rehabilitation through 1984

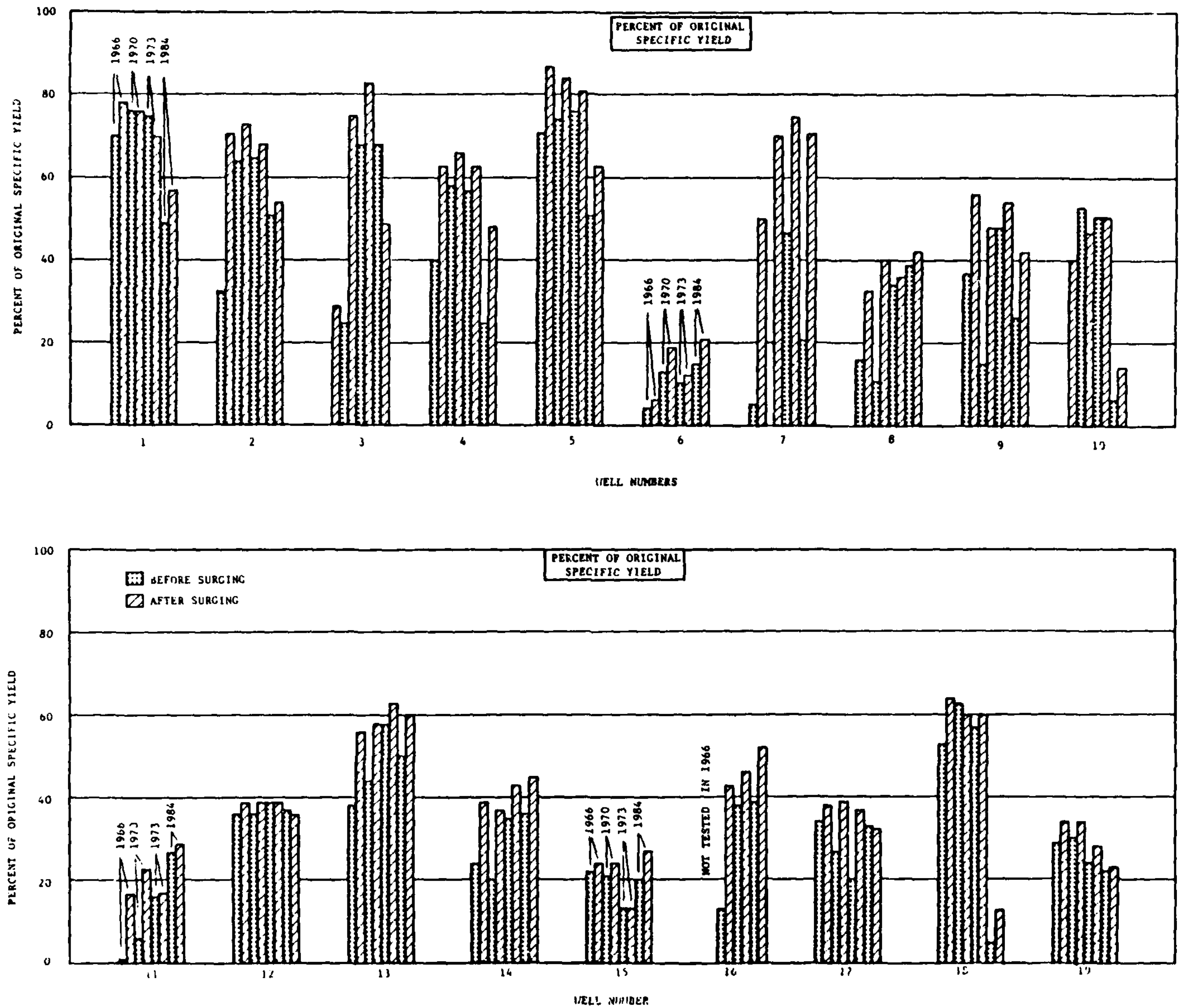

Figure 3. Specific capacity in percent of original, through 1984

capacity was only 41 percent of original compared with 50 percent in 1973. It is significant to note that wells 3, 10, and 18 lost more than an average of 60 percent of their specific capacity which accounts for half the overall loss. Possibly the most significant phenomenon in the 1983-1984 effort is seen in wells 6, 8, 11, and 15, the wells which were treated with acid 10 years previous. The 1983-1984 "preactivity" specific capacities were significantly higher than the "postactivity" specific capacities seen in 1973.

8. Data on these wells were submitted to Johnson Division for recommendations for future treatment. Mr. Glen Carpenter responded with questions about the 1973 water sample analysis, he believed the indicated iron contents were not possible. He suggested treatment with sulfamic acid because it is more selective in attacking the iron. He suggested extensive sulfamic acid treatments consisting of repeated applications to push the acid progressively further into the formation. He suggested alternate cycles using chlorination, acidizing, and hydraulic jetting. He recommended monitoring the effort using abbreviated pumping tests between cycles. He further suggested that pumping from the well during all surging and jetting operations is extremely important.

9. Conclusions are few. Time takes a toll which is not totally reversible, regular treatment is therefore advisable. Chemical treatment specific to the problem may have long term merit which may not be immediately apparent. There are many unknowns and much reason for research. These wells are ideal candidates for study since they are located in close proximity to the WES facilities; construction is representative of wells in many Corps of Engineers installations; problems are representative; the wells are well aged but structurally sound; and the history and performance record is well documented. The underdrainage system in the overbank structure was overdesigned and the realistic project flood has been reduced by subsequent downstream construction. Consequently, loss in well efficiency through experimental efforts would not jeopardize the stability of the structure.

CECIL M. HARDEN DAM TOE DRAIN REPAIR

Eugene Miller
US Army Corps of Engineers
Louisville District

1. Cecil M. Harden Dam was completed in July 1960 and consists of an impervious embankment on a pervious foundation. There is no internal drainage system within the embankment section. Eight, 12-in. bituminous corrugated metal relief wells to bedrock were constructed under the original dam contract. These wells were placed on 100-ft centers and were installed by the reverse rotary circulation method.

2. Excessive seepage was observed at the downstream toe of the dam in June 1961. Subsequent field inspection noted boils in the vicinity of relief wells 5 and 6. Generally, all eight relief wells were flowing; well 5 was at or near maximum capacity. Construction of a toe drainage system was begun in August 1962 and completed in October 1962.

3. The toe drainage system consisted of a 14-gage, 24-in. perforated corrugated metal pipe with drain holes at the bottom only. This pipe extended some 900 ft along the toe of the dam just downstream of the existing relief wells. The pipe was surrounded by a 2-ft minimum thickness of filter material. Four corrugated 36-in. metal manholes were provided along the length of the toe drainage system. An outlet headwall with flap gate was constructed just downstream of the stilling basin and provided the means for monitoring the flows from the toe drainage system.

4. After construction of the drain the bulk of the flow occurred at depths of 20 to 40 ft in all wells. This corresponds with previous piezometer readings except for well number 5. Prior to construction of the toe drain relief well number 5 had 30 to 37 percent flow concentration at the top just beneath the riser pipe which is 8 ft long. After installation of the drain, well number 5 had only 5 percent flow at the top and 63 percent of the flow was concentrated between 20 and 35 ft deep. The area below the dam completely dried up and was used for recreation.

5. During the periodic inspection of September 1967 surface seepage was visible in a low area from well 5 to halfway between wells 6 and 7. Little, if any, change was noted during the inspection of July 1972. During the

inspection of April 1977, however, seepage in the vicinity of relief wells 5 and 6 had increased significantly. Water was standing adjacent to well 5 and the area between the embankment and wells 5 and 6 was wet and very soft. Adjacent to these wells water was bubbling up through holes in the bottom of the metal flume.

6. In November 1977, an attempt was made to expose the perforated pipe in the vicinity of relief well 5 (Figure 1). A 3-in. pump and a 2-1/2-in.

Figure 1. Construction area from top of dam

pump were installed in relief well 5 and another 2-1/2-in. pump was installed in relief well 4 to lower the ground water. All three pumps were operated around the clock for 2 days lowering the water about 3.5 ft below the ground surface which made the area dry and firm enough to support a backhoe. There was approximately 2.5 ft of clay cover overlying clean gravelly sand. The top of the drain (Figure 2) was located 5.7 ft below the surface. A 3-in. pump was used to pump water from the excavation. However, due to caving and excessive infiltration, the entire pipe could not be exposed. The only water entering the pipe was at the joints, indicating that the perforations were plugged (Figures 3 and 4). The pipe was in excellent condition. The filter

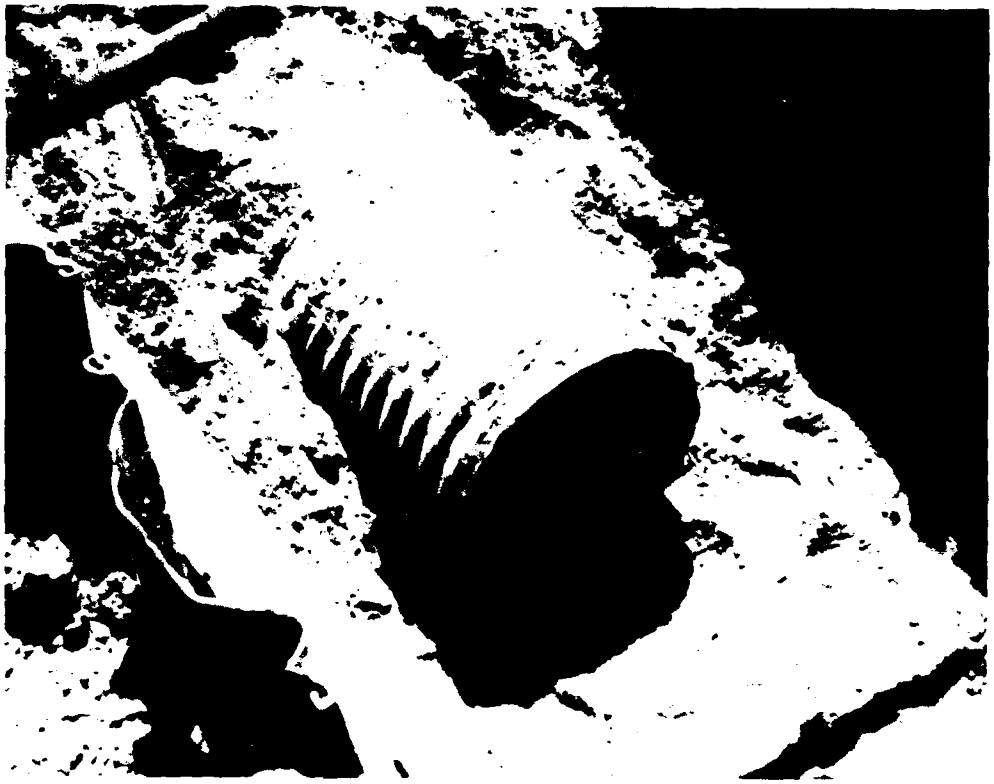

Figure 2. Old 24-in. BCCMP toe drain prior to removal; perforations were plugged and the filter that surrounded the pipes was dirty

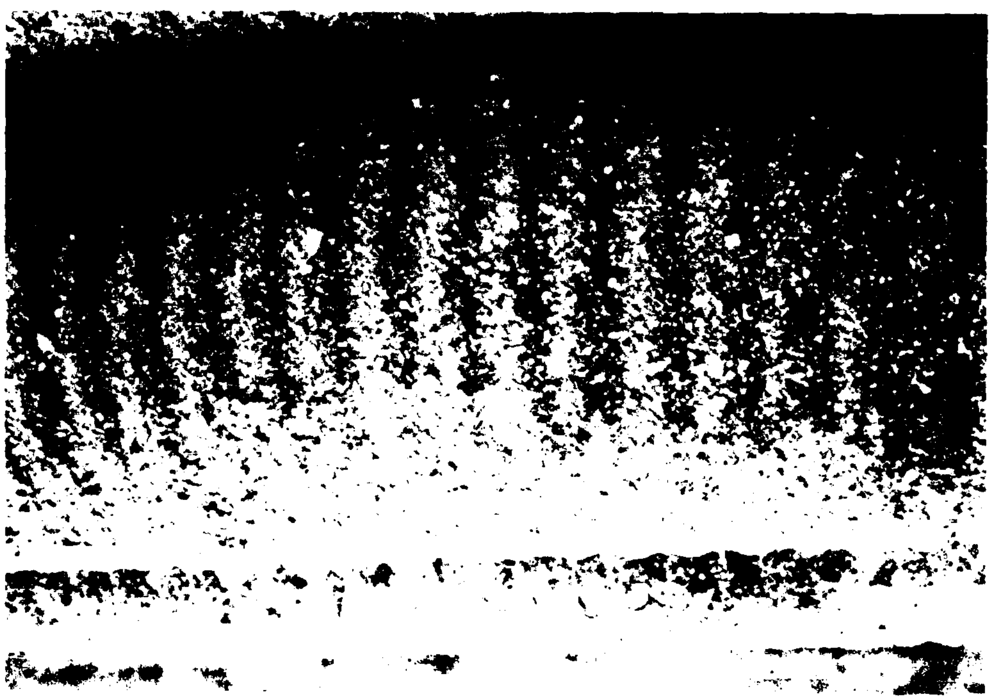

Figure 3. Old 24-in. BCCMP from toe drain; perforations are essentially plugged due to incrustation

Figure 4. Old 24-in. BCCMP toe drain pipe after removal; note condition of the inside pipe

material specified and actual gradation obtained in the excavation were as follows:

Sieve Size	Percent Passing Specified	Actual
1-1/2 in.	--	100
1 in.	100	97
3/4 in.	85-100	92
3/8 in.	60-85	78
No. 4	45-70	63
No. 16	20-45	38
No. 100	0-3	4
No. 200	--	3

7. It was proposed to replace the 24-in. perforated drain between manholes 1 through 4 with 16-in. PVC slotted well casing and move the outlet approximately 300 ft downstream. A trench approximately 6-ft wide was required for removal and installation procedures (Figure 5). A well point system along the toe was requested. Pumping of the existing relief wells up to 1 cfs was permitted. Shoring and bracing was required for all excavations and removed when the installation was completed. The existing manholes were used. The discharge pipe from manhole 1 to the retreat channel was constructed using salvaged 24-in. pipe from the existing toe drain. This pipe

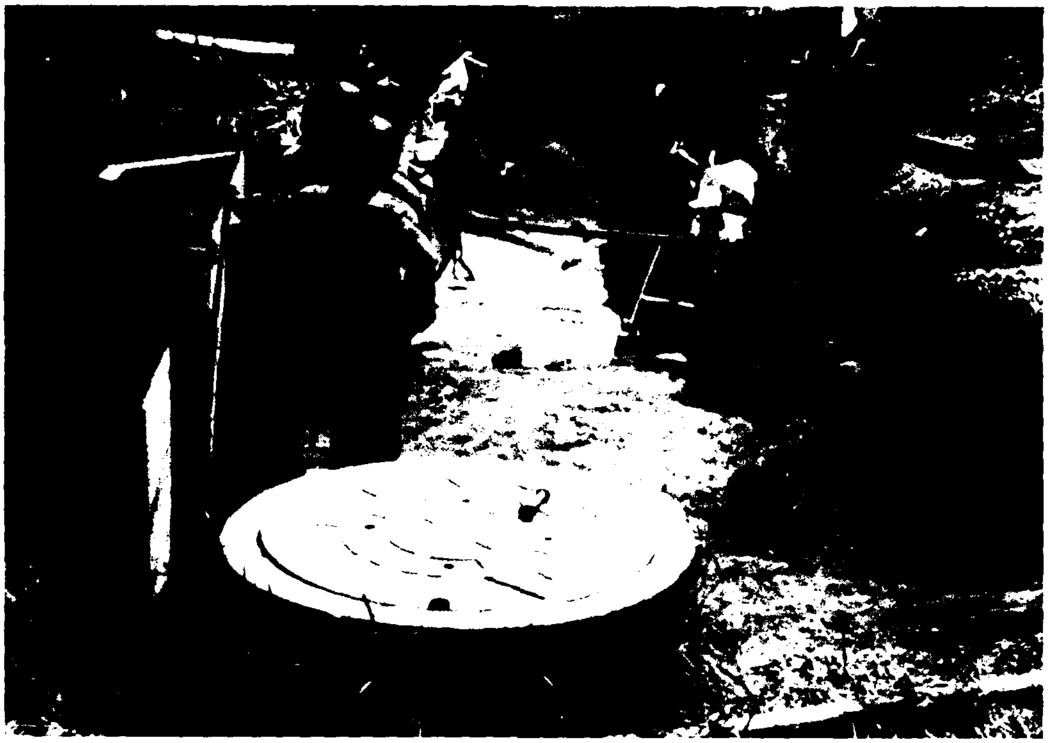

Figure 5. Excavated trench being prepared for new pipe; manhole No. 3 is in foreground and the old pipe is visible at the end of the trench

was placed with perforations at the top to minimize infiltration. The 16-in. PVC Jet Stream 20 Plus (Figure 6) slotted well casing has 33 sq in. open area per ft length with slots approximately 0.085 in. wide and 4.25 in. long. The well casing is surrounded by a 2-ft minimum thickness of Indiana No. 8 coarse aggregate filter enclosed in filter fabric (Figure 7). The filter fabric met chemical, physical and manufacturing requirements in accordance with ASTM standards. The filter material for the toe drain met the following gradations.

	Percent Passing
Sieve Size	Specified
1 in.	100
3/4 in.	85-100
1/2 in.	25-55
3/8 in.	8-25
No. 4	0-5

8. The new toe drain and the relief wells appear to be adequately controlling the underseepage beneath the dam.

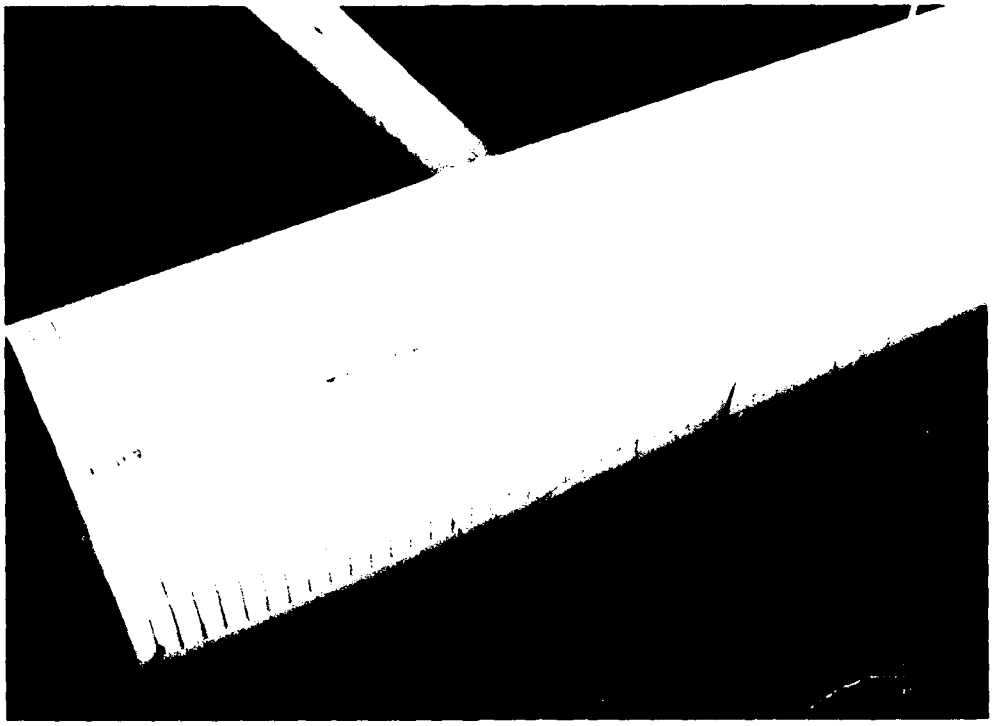

Figure 6. New 16-in. diam Jet Stream 20+ slotted well casing; open area is 33 sq in./ft of length

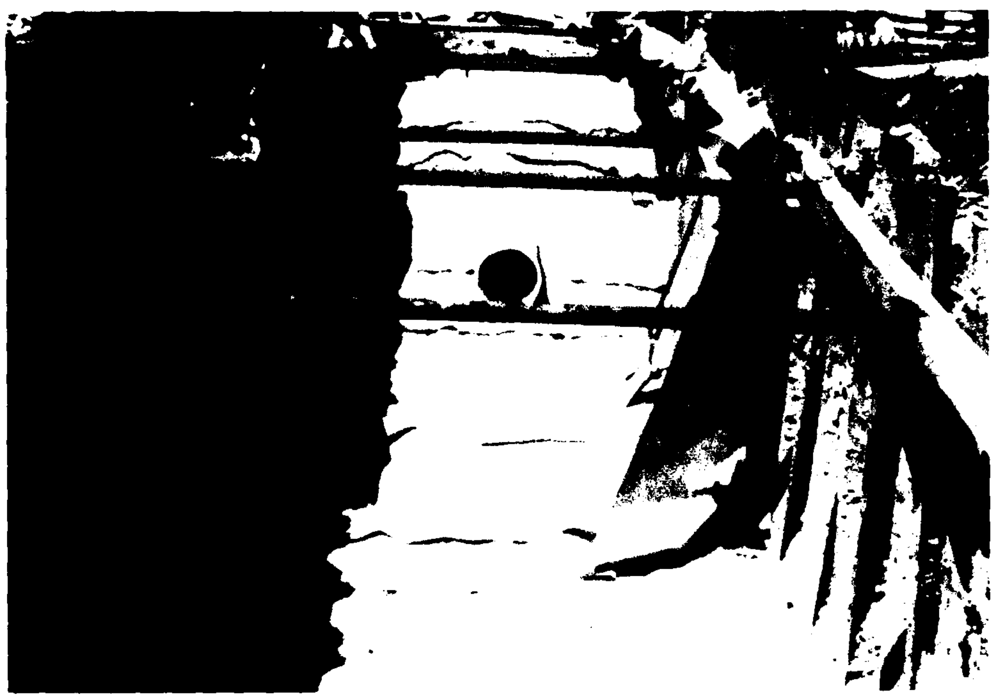

Figure 7. New 16-in. slotted PVC pipe after placement in trench; DuPont Typar geotextile separated the No. 8 coarse aggregate and in situ soil

SUMMARY OF PROBLEMS/PRIORITIES

1. On the basis of the presentations made during the workshop it appears that rehabilitation of drainage systems and relief wells is a matter of major concern in CE Districts. Information is lacking on the nature of the clogging mechanism and therefore how best to increase the effectiveness of the drainage systems and relief wells. Clogging due to infestation by iron bacteria seems to be the major cause of reduced efficiency. A major problem is the fact that many existing wells that consist of wood stove pipe are more difficult to rehabilitate than newer wells. More recently installed plastic well screens are also sensitive to the rugged mechanical action employed in rehabilitation efforts. Current maintenance rehabilitation procedures in the Districts vary widely.

2. Information on effective maintenance is lacking, methods for identifying the clogging mechanism and for choosing the proper mechanical and chemical treatments need to evaluated, and results should be disseminated to the Districts. Information on innovative methods of rehabilitation should be brought to the attention of the Districts on a timely basis.

3. Improved check valves and flap gates are a necessity to minimize problems with backflow. Vandalism is a continuing problem and should be considered in the restoration of existing facilities.

4. At the conclusion of the workshop, the attendees were requested to indicate priorities for future research in the area of drainage system and relief well problems. The priorities were indicated on the handout shown as Figure 1. The results of the survey are presented below.

RESTORATION OF DRAINAGE SYSTEMS

5. Clogging of underdrains at the base of concrete gravity dams or in rock is a problem in several Districts. Generally, the drains are reamed or redrilled on a as-needed basis or 5-year interval. Despite substantial maintenance costs, no suggestions for improving rehabilitation work were advanced.

6. Improved check valves and flap gates are a necessity to minimize problems with backflow into drainage systems. Vandalism is a continuing problem and should be considered in the restoration of existing facilities.

Name and Organization:

I. Restoration of Drainage Systems:

Problem for your Division/District	Current/Potential Solution	Per Year Occurrence	Per Year Cost
1.			
2.			
3.			
4.			
5.			
6.			

II. Restoration of Relief Wells:

Problem for your Division/District:	Current/Potential Solution	Per Year Occurrence	Per Year Cost
1.			
2.			
3.			
4.			
5.			
6.			

III. Potential Projects for Demonstrating REMR Techniques:

Type Problem	Project Name and Location
1.	
2.	
3.	

Figure 1. REMR workshop priorities for drainage system and relief well problems

Drainage system areas of interest encountered by the authors are presented below:

- a. Wall drain problems; evaluation and rehabilitation.
- b. Improving subsurface and underwater drains including downstream drainage blankets and effectiveness of gabbions; evaluation and rehabilitation.
- c. Maintenance guidance.
- d. Surface drainage guidance for low grades.
- e. Improvements in drain outlets, i.e. check valves and flap gates.
- f. Geotextile guidance for drains including concrete lined drainage ditches.
- g. Innovative drainage products and techniques.

7. At the conclusion of the workshop, the attendees were requested to indicate priorities for future research in the area of drainage system problems. The problem areas for drainage systems are listed below by those most often mentioned in the responses:

- a. Evaluation and rehabilitation of deep horizontal and vertical drains.
- b. Geotextile guidance for drains.
- c. New products information; technology transfer.
- d. Evaluation of subsurface drainage problems.

RESTORATION OF RELIEF WELLS

8. The dissemination of information on well maintenance, including monitoring procedures, identification of clogging mechanisms, and procedures for rehabilitation, appears to be the matter of highest priority. The need for improved procedures incorporating innovative techniques was recognized.

9. The rehabilitation of wooden relief wells pose special problems because of their sensitive character. Districts need better guidance, determined by REMR case history studies, on selection of replacement wells including appropriate screen sizing and gravel pack selection. Improved designs for relief well check valves and flap gates are considered of vital importance.

10. The need for demonstration projects where innovative rehabilitation techniques could be evaluated was urged. The development of small well flow meters that could be used in partially blocked wells was suggested. A study

to determine why pressure relief wells in the St. Louis District were regenerated after being flushed by high water was suggested.

11. A summary of the concerns generated by the workshop participants, tabulated from questionnaires completed after the presentations, was prioritized and presented to the group as research areas. The list is as follows:

a. Information on present and innovative procedures on maintenance and on use of chemicals.

b. Guidance on inspection and evaluation methods.

c. Other more specific items:

(1) Iron bacteria maintenance.

(2) Check and flap valves.

(3) Wood stave replacements.

(4) Small flow meters.

(5) Vandalism.

(6) Exploration techniques (hydrogeology).

APPENDIX A

IRON BACTERIA OCCURRENCE, PROBLEMS AND POTENTIAL SOLUTIONS IN WATER WELLS

by

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PART I: INTRODUCTION

Objectives and Scope

1. This report represents a state-of-the-art document on iron-precipitating bacteria in ground water and wells. The basic objective of this document is to review what is currently known about the nature and occurrence of iron-precipitation bacteria in ground water so that this information might be utilized to guide the development of effective strategies for controlling the growth of these bacteria in wells. "Iron-precipitating" bacteria include a wide variety of different organisms. Information on the physiology and ecology of this diverse group of bacteria is presented along with a review of the problems attributed to the growth of iron-precipitating bacteria in wells. Control measures used to rehabilitate wells clogged with the troublesome accumulation of these bacteria and their associated iron deposits are also discussed.

2. This document was prepared to assist government officials, engineers and ground-water industry representatives who have an interest in the problems associated with iron-depositing bacteria in wells and who are either responsible for or involved in well maintenance and rehabilitation practices. Impetus for the development of this report was provided by a US Army Corps of Engineers research program addressing the repair, evaluation, maintenance, and rehabilitation needs of older hydraulic structures constructed as part of the Corps civil works program. One aspect of this research program has been concerned with the maintenance needs associated with relief wells and underground drainage systems which are installed as appurtenant structures to dams and levees. The decline in efficiency of these wells and drains as a result of clogging by iron-precipitating bacteria has been regarded as a common and routine maintenance problem. Efforts are therefore underway to identify effective treatment methodologies for keeping these relief wells and drainage systems free from iron-precipitating bacteria and to maintain these wells and underground drainage systems in optimum operating condition.

Background

3. Since the mid-nineteenth century, certain filamentous bacteria have been recognized for their ability to remove iron from solution by precipitating insoluble ferric hydroxide outside their cells (Harder 1919). These "classical" iron-precipitating bacteria include the stalked *Gallionella* species and members of the *Sphaerotilus-Leptothrix* group of filamentous iron-precipitating bacteria. Subsequent studies of bacterial iron transformations in water, however, have shown that the deposition of insoluble ferric hydroxide is associated with an even more heterogeneous group of bacteria, including many nonfilamentous forms, such as the encapsulated *Siderocopsa* species (Starkey 1945). Although the bacteria associated with iron precipitation in water are commonly referred to as "iron bacteria," this is a general term used to describe a diverse group of organisms which occur in a wide range of habitats including lakes, ponds, swamps, bogs, drainage ditches, and chalybeate springs (Ghiorse 1984).

4. In addition to their ability to deposit ferric hydroxide around their cells, various iron bacteria are also capable of excreting extracellular polysaccharides which have been variably described in the literature as gelatinous, mucilaginous or slime-like substances (Gaudy and Wolfe 1962). This extracellular material coats the external surface of the organism's cell well or sheath and serves as a site for the accumulation of precipitated ferric hydroxide. Over time, this extracellular material may become impregnated and encrusted with iron oxides resulting in a brown to reddish colored slimy mass which typifies the growth of iron-precipitating bacteria in natural environments.

5. Iron bacteria which occur in water-distribution systems, wells, and underground drains are considered significant fouling agents as a result of their dual ability to excrete extracellular slimes and to precipitate large amounts of ferric hydroxide. Historically, prolific growths of filamentous iron bacteria in water supply systems have been called "water calamities" (Starkey 1945). In these instances, the gelatinous growth of iron bacteria and their associated deposits of ferric hydroxide have resulted in discolored water, unpalatable taste and odors, and reductions in flow through pipes. Additionally, iron bacteria have been implicated as indirect agents of corrosion in water distribution pipes as a result of their ability to create a

suitable growth environment for other organisms directly involved in metal corrosion processes (Starkey 1945).

6. Iron bacteria infestations in water wells are regarded as the most prevalent cause of bacterial degradation of well performance (Smith 1984). These infestations are often characterized by a severe and rapid clogging of the well screen openings and the pores of the materials su.rounding the well bore (Mogg 1972). This physical blockage of the well intake area results in decreased hydraulic efficiency, manifested by significant reductions in specific capacity. In severe cases, steel well components may be corroded anodically and tuberculated (Smith 1980).

7. A quantitative survey of the economic impact of iron bacterial well degradation has never been conducted, although a survey of water authorities by Cullimore and McCann (1977) demonstrated worldwide familiarity with the problem. Reports describing the occurrence and effect of iron bacteria growth in wells have been published periodically and involve locations as geographically diverse as Germany (Hasselbarth and Ludemann 1972), Yugoslavia (Barbic et al. 1974), India (Roa 1970), Finland (Tuovinen and Nurmiaho 1979), and North America (Cullimore and McCann 1977). In addition to these widespread reports, representatives of the water well industry involved in well rehabilitation work have speculated that iron bacterial populations are spreading (Mogg 1972). This speculation, however, is based on empirical observations rather than on a quantifiable assessment of iron bacteria in aquifers.

8. Despite this overall awareness of the iron bacterial problem in wells, there is a paucity of knowledge regarding effective methods for treating wells contaminated with these nuisance organisms. Throughout the published literature, the description of remedial treatment methods used to control iron bacteria in wells are frequently anecdotal and the techniques used are often lacking scientific investigation. Grainge and Lund (1969) noted that there was a proliferation of recommended controls for iron bacteria in wells, however, they found most of these methods to be ineffective. They further concluded that this lack of advancement in control strategies for iron bacteria was due to the difficulties in culturing iron bacteria for experiments.

9. The problems associated with culturing various iron-precipitating bacteria on laboratory media have been extensively reviewed in the literature (Pringsheim 1949). Because there are no known simple procedures for

cultivating many of these organisms in the laboratory, most studies have been limited to microscopic observances (Starkey 1945). As a result, detailed information on these organisms is usually in regards to their physical structure (morphology) as opposed to their metabolic or growth requirements (physiology).

10. In general, the role which iron plays in the metabolic function of iron bacteria is poorly understood and is the subject of conflicting ideas in the research literature. In a review of the historical literature on iron bacteria, Pringsheim (1949) indicated that the metabolic controversy originated from two opposing postulates which were based on early cultural studies of iron bacteria in the late 1800's. Winogradsky postulated in 1888 that iron bacteria were chemoautotrophs; therefore, they utilized the energy released by the oxidation of ferrous iron to ferric iron in order to assimilate inorganic carbon for cell growth and development. Later research by Molisch in 1892 and 1910, however, showed that some iron bacteria grew well heterotrophically; therefore, they used organic carbon for an energy source and cell development. As a result of the research of Molisch, it is the contention that many, if not most, of the iron bacteria live on organic materials and effect the precipitation of iron incidentally during their growth. Although it is recognized today that not all iron precipitation bacteria are alike physiologically, this general controversy over the chemoautotrophic versus heterotrophic growth requirements of many specific iron-precipitating bacteria continues.

11. Though knowledge of the specific aspects of iron deposition by these bacteria may not be necessary for dealing with their troublesome accumulations in wells, more definitive information on the physiology and ecology of iron bacteria could help to guide the development of effective control strategies. By reviewing what is known about the specific growth requirements of various iron bacteria genera and by identifying key environmental conditions for their occurrence in ground water, control strategies may be better directed toward the destruction of the organisms themselves or the alteration of ground water and well environments so as to be unfavorable for their growth. Any means which can be used to prevent their development may be expected to aid in preventing fouling.

Discussion of Major Works

12. Current knowledge of the nature and occurrence of iron bacterial populations in ground water and wells is based on a relatively small body of literature. Researchers in this field typically cite older studies when compared to more active areas of microbial ecology research. This seems to be due to the lack of systematic study of iron-precipitating bacteria over the years. References on the subject are oftentimes obscure. Nevertheless, a number of available studies on iron bacteria are consistently cited in the literature and serve as primary references for what is presently known about the physiology and ecology of these organisms.

13. A monograph by Harder (1919) on the potential role of iron bacteria in the formation of iron-bearing ores represents the earliest known comprehensive study of the environmental occurrence of iron-precipitating bacteria. Although much of the taxonomic, morphologic, and physiologic terminology used in this report is outdated an inaccurate by modern day standards, Harder presented some solid observations and postulates regarding the nature of these organisms. He observed and concluded that: (a) iron-depositing bacteria are ubiquitous in the iron-bearing water of mines, wells, and springs; (b) common bacteria in water and soil, other than the classical filamentous iron bacteria, are capable of precipitating iron from solutions containing iron salts of organic acids; and (c) these organisms are capable of being introduced into fissures or other large underground openings by surface waters infiltrating through larger soil and rock openings. Harder contended that these subsurface populations of iron bacteria are responsible for the deposition of iron-bearing sedimentary and bog ores. This postulate still represents the basis for some present-day views that iron bacteria are indigenous to certain underground formations which also serve as aquifers.

14. Starkey (1945) presented the earliest known comprehensive review of iron-precipitating bacteria in water distribution systems. This article, still used as a primary reference for water system workers (Smith 1982), contains a clear discussion of the physiological aspects of bacterial iron transformations, including iron deposition by nonspecific heterotrophic bacteria as well as by the classical filamentous iron bacteria. Starkey also introduced the concept that bacterial iron hydrates on iron and steel provided a suitable substrate and anaerobic microenvironment for the growth of sulfate-reducing

bacteria which are responsible for metal corrosion. He further acknowledged the difficulty of culturing iron bacteria in laboratory media and pointed out that the study of these bacteria may be limited only to microscopic observations.

15. Pringsheim (1949) provided the first critical review of the historical literature on iron bacteria. Noting the existence of "a vast literature of unequal value," Pringsheim attempted to separate established facts from what he perceived to be an overwhelming mass of rash and controversial statements about iron bacteria. He discussed in detail the problems involved in the cultural investigation of these organisms as well as the unresolved controversy over the chemoautotrophic versus heterotropic theory of iron bacteria growth. Pringsheim also attempted to simplify the taxonomy of iron bacteria by inserting all the members of the *Sphaerotilus-Leptothrix* group of sheathed bacteria into one genus, *Shaerotilus*, recognizing only two species, *S. natans* and *S. dicophorus*. In doing so, however, he created some new problems in nomenclature. Later researchers rejected Pringsheim's taxonomic scheme in favor of one in which the general *Sphaerotilus* and *Leptothrix* were maintained (van Veen et al. 1978).

16. Procedures for culturing the classical stalked iron bacteria *Gallionella*, which is common in well clogging problems, have been the subject of numerous studies. Kucera and Wolfe (1957) were successful in formulating such a media which was subsequently improved by Wolfe (1958) to enable continuous subculturing of *Gallionella* in the laboratory. Wolfe reported, however, that he was unable to achieve pure cultures of *Gallionella* with this medium due to a small but persistent growth of *Pseudomonas*. Two reports of successful pure cultures of *Gallionella* were published in 1968 (Hanert 1968, Nunley and Krieg 1968). Hanert used Wolfe's medium without sugar and claimed pure cultures by serially diluting out contaminants. Nunley and Krieg employed Wolfe's medium containing 0.5 percent formalin which produced cultures without contamination in seven out of ten trials. Subsequent attempts by other researchers to corroborate both these isolation techniques, however, have failed (Christian 1975).

17. Hasselbarth and Ludemann (1972) published the earliest known aquifer-wide environmental research involving an iron bacteria problem in wells. They examined municipal wells located within six water catchment areas in Germany which were experiencing bacterial encrustation problems resulting

from the growth of *Gallionella* and *Siderococcus* species. By comparing the ground water quality between these wells located within two other water-catchment areas which were not experiencing iron bacterial problems, they concluded that the mass development of iron bacteria in wells was a function of the chemical nature of the well water. They found that massive growth was associated with well water having specific pH, Eh (oxidation-reduction potential) and dissolved ferrous iron range. Hasselbarth and Ludemann concluded that four conditions were necessary for iron bacterial clogging of wells: (a) the presence of iron bacteria; (b) specific dissolved ferrous iron concentrations; (c) specific Eh and rH index (an adjusted oxidation-reduction potential taking into consideration temperature and pH values) ranges; and (d) elevated ground-water flow velocities, which are common at well intakes.

18. Valkenburg et al. (1975) reported on a state-wide survey of 109 wells in Alabama which were sampled to determine the occurrence and distribution of iron bacteria. In the majority of samples collected, *Gallionella* and/or *Sphaerotilus* species were identified both microscopically and by cultural methods. At least one genera of iron bacteria was found in 27 of the 35 counties where samples were collected, demonstrating widespread occurrence of these organisms through Alabama aquifers. Valkenburg et al. (1975) compared the occurrence of iron bacterial populations to well depth and water chemistry parameters, including temperature, dissolved ferrous iron, pH, conductivity, and dissolved oxygen. Selected bacteriocides and heat treatments for controlling *Gallionella* were also tested under laboratory conditions. Valkenburg et al. argued that iron bacteria are probably introduced into wells from the surface and not via the water-bearing zone, thus implicating drilling and well service contractors as the primary factor for the spread of iron bacteria. They recommended well drillers use clean drilling water, circulation tanks, and standard development techniques when constructing wells and that all completed and repaired wells should be properly disinfected in order to prevent the future spread of iron bacteria.

19. Cullimore and McCann (1977) discussed extensive iron bacteria research which had taken place at the University of Regina in Saskatchewan since 1971. The research was initiated in response to an intractable iron bacterial problem that affected over 90 percent of the wells across the southern half of Saskatchewan, resulting in remedial measures costing four to six million dollars annually. The predominant genera of iron bacteria

identified in the well clogging problems were *Crenothrix*, *Leptothrix*, *Gallionella*, and *Sphaerotilus*. Cullimore and McCann reviewed a variety of chemical and physical iron bacteria control measures which were the subject of a series of later reports (Cullimore 1971a,b). Based on field trials, they reported that the heat treatment of wells represented a promising method for rehabilitating wells clogged with iron bacteria. By raising ground water temperatures to near pasteurization levels, they indicated that iron bacterial growths, which had previously resisted chemical treatments, were successfully removed from wells.

PART II: CLASSIFICATION AND OCCURRENCE

Taxonomy

20. According to Bergey's Manual of Determinative Bacteriology (1974), eighteen genera of bacteria have been characterized as having the ability to deposit ferric hydrate outside their cells. These genera represent a diverse group of bacteria with differing morphology and metabolic capabilities as well as widely varying habitats (Table 1). The ability to precipitate iron from solution has apparently evolved among many unrelated organisms. In the past, it has been generally assumed that the iron has played some role of importance to the cells preceding its precipitation.

21. Despite this general listing of bacteria associated with iron deposition, the taxonomy or classification of iron bacteria can best be described as intricate and disputed. As an example, one group in Bergey's Manual (1974), the Siderocapsaceae family comprising the four genera *Siderocapsa*, *Naumanniella*, *Ochrobium*, and *Siderococcus*, has been questioned as to its validity as a taxonomic unit. The editors of Bergey's Manual (1974) note that recent research showed some *Siderocapsa* species were indistinguishable from *Arthrobacter* species and that *Ochrobium* may in fact be an alga. They further note that despite including this family with the chemolithotrophs, members of the family are heterotrophic, depositing iron only as the result of the metabolism of the organic ion portion of iron salts of organic acids. As a result, it is easy to see that the taxonomy of this group is in disarray and requires further study.

22. In addition to disputed taxonomy, contradicting nomenclature used to describe certain genera of sheathed bacteria has caused problems when reviewing the literature on iron bacteria. The cause of the nomenclature problem was the demonstration by Pringsheim (1949) that forms of the sheathed iron bacteria could change under different culturing conditions in the laboratory. As a result of his observations, Pringsheim argued that most forms previously designated as various species of *Leptothrix* and *Clonothrix* should be included in the genus *Sphaerotilus* along with *S. natans*. He proposed abolishment of the genus names *Leptothrix* and *Clonothrix* and recognized instead only two species; *S. natans* and *S. discophorus*. *S. discophorus* was distinguished by its ability to deposit ferromanganese oxide in the sheath, while *S. natans*

Table 1

Genera of Bacteria That Become Coated or Encrusted With Iron Deposits (after Bergey 1974)

	Genus	Notes
Gliding bacteria	*Toxothrix*	No pure cultures; found in cold springs, bogs, ponds, and lakes containing ferrous iron
Sheathed bacteria	*Sphaerotilus*	Pure cultures of some species claimed; found in slowly running water attached to submerged plants and rocks; occurs in activated sludge
	Leptothix	Pure cultures of some species claimed; found in slowly running waters attached to submerged rocks and plants; growth causes problems in water works
	Lieskella	No pure cultures; found in upper layers of mud in bodies of water
	Crenothrix	No pure cultures; found in stagnant and running waters containing organic matter and iron salts
	Clonothrix	No pure cultures; found attached to iron fittings in well waters
Budding and/or appendaged bacteria	*Gallionella*	Pure cultures claimed; found in ferrous iron-bearing waters and soils; growth causes problems in water works
	Pedomicrobium	Pure cultures; found widely distributed in soil and water
	Seliberia	Pure cultures; common inhabitant of soils
	Planctomyces	No pure cultures; found in surface layers of lakes
	Metallogenium	Pure cultures; found in soil and water
	Caulococcus	No pure cultures; found in bottom mud of lakes
	Kusnezovia	No pure cultures; found in mud samples from lakes
Gram-negative, chemolithotrophic bacteria	*Thiobacillus*	Pure cultures; found in acid waters of high iron content and in soils containing pyrite and marcasite
	Siderocapsa	No pure cultures; common in fresh water
	Naumanniella	Pure cultures; widely distributed in iron-bearing waters
	Ochrobium	No pure cultures; widely distributes in iron-bearing waters
	Siderococcus	No pure cultures; widely distributed in fresh waters and bottom deposits

deposited primarily iron hydroxide. This nomenclature, however, has been disputed by Mulder and van Veen in their description of the sheathed bacteria in Bergey's Manual (1974). They contend that the diversity of the various species in this group is not in accordance with Pringsheim's simplified classification system and that they have shown that members of the *Sphaerotilus* and *Leptothrix* genera are distinctly different organisms. Since publication of the eight edition of Bergey's Manual (1974), Mulder and van Veen's classification of the *Sphaerotilus-Leptothrix* group has gained acceptance. However, such acceptance has not been universal (Ghiorse 1984).

23. It should also be realized that many of the problems facing the taxonomy of iron bacteria are the result of inability of researchers to isolate pure cultures of many of these organisms (Table 1). Without isolated cultures, these organisms can only be studied from environmental samples or enrichments of such samples by using microscopy. Therefore, detailed knowledge of various iron bacteria is often limited to structural features and this information has not always proved adequate for taxonomic purposes.

24. For the purposes of this report, the remaining focus will be on the taxonomic genera of iron bacteria which have been commonly observed in ground water and well environments. This mainly includes the stalked *Gallionella*, members of the sheathed *Sphaerotilus-Leptothrix* group and nonfilamentous, heterotrophic forms such as *Siderocapsa* and *Siderococcus*. This does not imply that the other organisms are not important in iron deposition. As an example, *Thiobacillus ferrooxidans* is a known chemolithotriphic iron bacterium which is acidophilic, and frequently associated with acid mine drainage (Bigham et al. 1985). Acidophilic bacteria, however, are rarely described as occurring in water well environments outside of those aquifers which might be affected by acid mine drainage. Investigators should be aware of the possibility of this or any other unusual ground-water condition when looking at iron bacteria problems in wells. However, it is unlikely that these or other unique iron-depositing species will be a prevalent problem.

Morphological Characteristics

25. The morphological (structural) characteristics of iron bacteria represent the major basis of identification and classification. Because of their size and unique extracellular structures, iron bacteria can often be

identified in water or substrate samples by light microscopy. Identification is made by comparing the microscopic images with available drawings or photographs of iron bacteria (Standard Methods 1976). Traditionally, the iron bacteria have been categorized into three morphological groups: stalked forms which are oriented from top to base; filamentous forms composed of chains of cells enclosed in a sheath; and typical shaped coccoid cells or short rods occurring in irregular aggregates (Starkey 1945).

26. *Gallionella* is the unique example of a stalked iron bacterium. These organisms are characterized by a small bean-shaped cell from which originates a long slender twisted stalk (Figure 1). The small oval cell is typically 0.5 × 1.2 microns in size and the ribbon-like stalk may attain a length of 200 microns or more. The composition of the stalk has been the subject of much study and controversy (Ghiorse 1984). Figure 2 is an electron micrograph showing the *Gallionella* apical cell, the area of fine fibrillar material near the surface of the cell and the dense stalk fibrils originating from the cell. Although it has been generally assumed that the *Gallionella* stalks were

Figure 1. *Gallionella* with their characteristic bean-shaped cells from which are excreted twisted stalks encrusted with ferric hydrate. Magnified approximately 1,180 × (Starkey 1945)

Figure 2. Electron micrograph graph of *Gallionella* showing bean-shaped cell and ferric hydrate coated stalk fibrils originating from it. Bar = 0.5 microns (Ghiorse 1984)

entirely inorganic extrusions of ferric hydrate, current research indicates that the stalk fibrils may contain protein to which the ferric hydrate is bound (Ghiorse 1984). Regardless the composition of the *Gallionella* stalk, the organisms grow attached to surfaces by their stalk and this sessile characteristic must be kept in mind when sampling for these bacteria (Hanert 1981a).

27. The filamentous forms of iron bacteria are represented by the members of the *Sphaerotilus-Leptothrix* group. These organisms are structurally characterized by filaments which are composed of a series of cells enclosed in a sheath (Figure 3). Studies of *Sphaerotilus natans* have shown that the sheath of this organism is composed of a protein-polysaccharide-lipid complex which is chemically distinct from the cell wall (Romano and Peloquin 1963). Little is known, however, about the chemical composition of *Leptothrix* sheaths. In addition to sheath structures, members of the *Sphaerotilus-Leptothrix* group excrete excellular polysaccharides which result in a cohering slime layer that covers the sheath (Gaudy and Wolfe 1962). Both the sheath and the slime layer of these organisms typically become encrusted with ferric

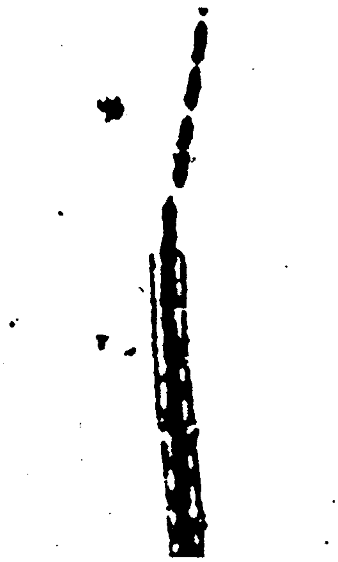

Figure 3. *Leptothrix* spp. filament comprised of a series of cells coming out of their sheath. Magnified approximately 2,200 *v* (Starkey 1945)

hydrate resulting in large masses of filamentous growth and iron deposits (Figure 4). Additionally, the sheaths of *Leptothrix*, especially if heavily impregnated with iron, are frequently empty (van Veen et al. 1978). The filamentous iron bacteria are also characterized by their sessile nature, with some species of the *Sphaerotilus-Leptothrix* group developing special holdfasts which are used to attach the organism to solid surfaces (van Veen et al. 1978).

Figure 4. Sheaths of *Leptothrix* from an accumulation of precipitated ferric hydrate in iron-bearing water. Magnified approximately 390 *v* (Starkey 1945)

28. The third morphological group of iron bacteria are comprised of nonfilamentous, unicellular bacteria which grow in irregular clusters (Figure 5). These organisms include members of the Siderocapsaceae family, particularly the genera *Siderocapsa*, *Naumanniella*, and *Siderococcus*. A common structural feature of this group is the development of an extracellular capsule composed of an excreted gelatinous material of unknown composition (Hanert 1981b). These slime-encapsulated bacteria are characterized by their ability to form large masses of ferric hydrate which impregnates the capsular material. Unlike the stalked and filamentous forms of iron bacteria, many of these unicellular organisms are planktonic, not sessile. In addition to the Siderocapsaceae family, Macrae and Edwards (1972) demonstrated that seven heterogeneous genera of unicellular, rod-shaped bacteria, including *Pseudomonas* and *Eschericha*, were capable of precipitating colloidal iron from solution by passively adsorbing the iron onto their cell walls. Where these heterotrophic bacteria occur in mixed populations with stalked and filamentous iron bacteria, they may also contribute to iron deposition and potential clogging problems (Smith 1984).

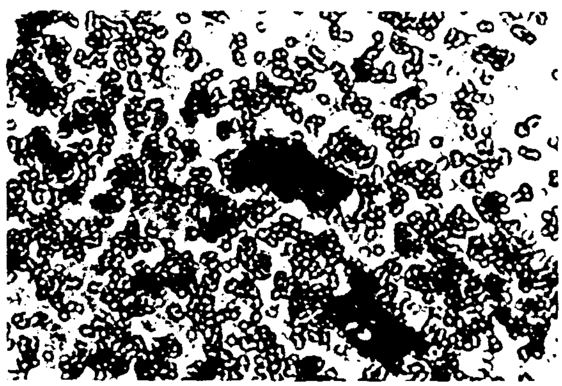

Figure 5. *Siderococcus* organisms showing coccoid forms in irregular clusters along with precipitated ferric hydrate (Hasselbarth and Ludemann 1972)

Physiological Characteristics

29. Despite numerous nutritional and physiological studies of various iron bacteria genera over the past one hundred years, many aspects of the

metabolic and growth requirements of these organisms remain unknown. Researchers often attribute this lack of progress to the failure to isolate axenic (pure) cultures of these organisms (Wolfe 1964). Without pure cultures for study, the incontrovertible evidence needed to resolve many physiological questions about iron bacteria cannot be easily obtained.

30. Oxidation of ferrous iron is often thought to be one of the most typical characteristics of iron bacteria genera. This characteristic is based on the original postulate by Winogradsky in 1888 that iron bacteria are chemoautotrophic (Pringsheim 1949). Winogradsky claimed that iron in the ferrous state is oxidized to ferric iron and that the energy obtained from this oxidation is used by the iron bacteria to assimilate or fix carbon dioxide into organic compounds necessary for metabolism. Although the precise mechanism for the biochemical oxidation of iron has never been confirmed, Baas-Becking and Parks (1927) proposed one reaction by which iron bacteria may live as chemoautotrophs:

$$4\ FeCO_3 + O_2 + 6H_2O \rightarrow Fe(OH)_3 + 4\ CO_2 + 81{,}000\ cal$$

31. Utilizing this equation, Starkey (1945) estimated that the growth of bacteria on ferrous iron in solution will result in an approximate 500 to 1 ratio of precipitated ferric hydrate to cell material. Wolfe (1964) suggested that the small amount of energy released by this exothermic reaction was responsible for the large quantities of ferric hydrate precipitated by iron bacteria.

32. Although the Winogradsky theory that iron bacteria are chemoautotrophic has received additional support from the results of other studies, the concept has not been universally accepted. In a review of the historical literature on iron bacteria, Pringsheim (1949) relates the details of other theories which have been advanced to explain the physiological deposition of iron by these bacteria. Molisch, in a series of studies from 1892 through 1910, was able to grow cultures of iron bacteria on organic medium, without the intentional addition of iron. He established for the first time that some iron bacteria were heterotrophic. Based on Molisch's results and later studies which have followed, researchers have shown that many of the iron bacteria are able to grow on organic material, and there is reason to believe that in the case of certain organisms classified as iron bacteria, precipitation of

iron is the result of the decomposition of organic compounds of iron and not the oxidation of inorganic iron compounds (Harder 1919). Recognizing the potential for both chemoautotrophic and heterotrophic growth among differing iron bacteria genera, Starkey (1945) concluded that where iron bacteria are the sole cause of a fouling problem, there will be an abundance of ferric hydrate with relatively few bacterial cells. However, if the clogging material was composed of large amounts of filamentous growth and slime with little accompanying ferric hydrate, then the bacteria probably developed on the organic constituents of the water or some material other than ferrous iron.

33. With regard to the iron bacteria genera which characteristically inhabit ground water and well environments, *Gallionella* species are generally considered to be chemoautotrophic, although some researchers believe that this has not been demonstrated conclusively (Ghiorse 1984). The best evidence of chemoautotrophic growth of *Gallionella* was presented by Hanert (1968) in which he used carbon 14 labelling to show that carbon dioxide was fixed (i.e. assimilated into organic compounds for metabolism) in measurable amounts by these organisms. Furthermore, *Gallionella* can [illegible]own on an inorganic medium containing mineral salts, carbon dioxide and ferrous sulfide, which is used as an energy source (Kucera and Wolfe 1957). Notwithstanding this evidence, Ghiorse (1984) argues that rigorous proof of chemoautotrophy in *Gallionella* is still lacking. One reason is that pure cultures of these organisms have not been easily obtained for study. Despite reports by Hanert (1968) and Nunley and Kreig (1968) claiming growth of pure cultures of *Gallionella*, their methods have not been corroborated by other researchers (Christian 197[illegible]). Secondly, research of chemoautotrophy in *Gallionella* has been impeded by abiotic ferrous iron oxidation which naturally occurs in the organism's growth environment. Since *Gallionella* is a microaerophillic bacterium and grows near neutral pH conditions, Kucera and Wolfe (1957) have suggested that the organism must compete with atmospheric oxygen for the oxidation of ferrous iron. This creastes a question as to whether the ferric hydrate precipitated during *Gallionella* growth is the result of either strict chemical or bacterial processes.

34. van Veen et al. (1978) reviewed the question of chemoautotrophy among members of the filamentous *Sphaerotilus-Leptothrix* group of iron bacteria. Similar to the problems encountered with *Gallionella*, they stated that the main experimental difficulty in testing members of this group for chemoautotrophy is that they are aerobic and grow between a pH of 6 and 8. At

these pH values, ferrous iron is readily oxidized to ferric iron nonbiologically, so that it is difficult to determine whether or not the bacteria contribute to the oxidation of ferrous iron. There are, however, many reported studies which have established that some of these organisms can grow on organic compounds and do require organic matter for growth (Starkey 1945, van Veen et al. 1978). Conversely, no modern studies have been conducted which show the ability of members of the *Sphaerotilus-Leptothrix* group to grow chemoautotrophically. van Veen et al. (1978) concluded that although the sheath of *Leptothrix*, and rarely *Sphaerotilus*, may be encrusted with ferric hydrate, it is unlikely that the bacteria oxidize iron or derive energy from such a process. Because both organisms grow at near neutral pH where ferrous iron is chemically oxidized to ferric iron, it is probable that the sheaths serve only as a site for the deposition of insoluble ferric hydrate.

35. Studies of the Siderocapsaceae family indicate an obvious dependence on organic material for growth (Hanert 1981b). In addition, no studies have ever reported the growth of these aerobic heterotrophs in inorganic media. A lack of pure cultures for most of the genera *Siderocapsa*, *Ochrobium*, and *Siderococcus* has resulted in very little being known about the nutritional and physiological requirements of these organisms. They are believed, however, to be involved in the precipitation of ferric hydrate as a result of metabolizing the organic carbon portion of iron humates in soil and water.

Environmental Conditions

36. Although the various genera of iron bacteria have been shown to vary physiologically with respect to their role in the precipitation of iron, there is no reason to doubt that these organisms characteristically become encoated with ferric hydrate and that their normal habitat is iron-bearing waters. In addition, the bacteriological precipitation of dissolved or suspended iron in water may also be accompanied by naturally occurring chemical changes and in some cases will compete with them (Mallard 1981). Therefore, in order to better define the relationships between iron bacteria and their potential development in ground water and well environments, the chemical variables influencing iron transformations in natural waters will be discussed in conjunction with the environmental conditions where iron bacteria are known to occur.

37. The principal chemical variables which influence iron solubility in natural waters include the pH and redox potential (Eh) (Hem and Cropper 1959). The terms "redox potential (Eh)," "oxidation potential," and "oxidation-reduction potential" are interchangeably used in the literature of water chemistry to represent the relative intensity of oxidizing and reducing conditions in solutions. Eh, simply defined, is the measure of the voltage resulting from the flow of electrons in solution and is influenced by the water temperature and the concentrations of electrically charged ions in solution. Positive values for Eh signify oxidizing conditions in a solution and negative Eh values represent a reducing environment. The effect of Eh and pH on iron, and the ranges in which particular ion or solids will be stable at chemical equilibrium, may be depicted in a stability field diagram or "Eh-pH diagram" (Figure 6). The shaded regions of the diagram depict conditions where insoluble compounds of iron will occur and the unshaded regions represent conditions where dissolved iron forms are predominant. The upper and lower diagonal boundaries across the diagram represent the area in which a water is chemically stable. Above the upper boundary line water is oxidized to form oxygen gas and below the lower boundary line water is reduced to form hydrogen gas. It should be noted, however, that Eh-pH diagrams are theoretical and are calculated on the basis of selected conditions for temperature, pressure and ionic concentrations. Therefore, a stability field diagram may not reflect an actual situation because the assumptions made in the preparation of the diagram may not be representative of the site. Nevertheless, the diagram is a useful and convenient device for summarizing the aqueous chemistry of iron in solution and solid phases (Hem 1970).

38. Based on the Eh-pH diagram for iron shown in Figure 6, it can generally be concluded that when the Eh and pH of a solution are low, the solubility of iron is high. Conversely, the higher the pH or Eh value, the lower the solubility of iron. As a general reference, water in contact with air will have an Eh of approximately 0.35 to 0.50 V, and usually a pH greater than 5 (Hem 1970). Under these conditions, the stable form of iron is ferric hydroxide or ferric oxide and iron solubility is low.

39. The chemical principles, as represented in the Eh-pH diagram, exert a well-defined control over the solubility of iron in ground water. Ground water with a pH between 6 and 8 can be significantly reducing where groundwater flow precludes the entrainment of oxygen into the water and where

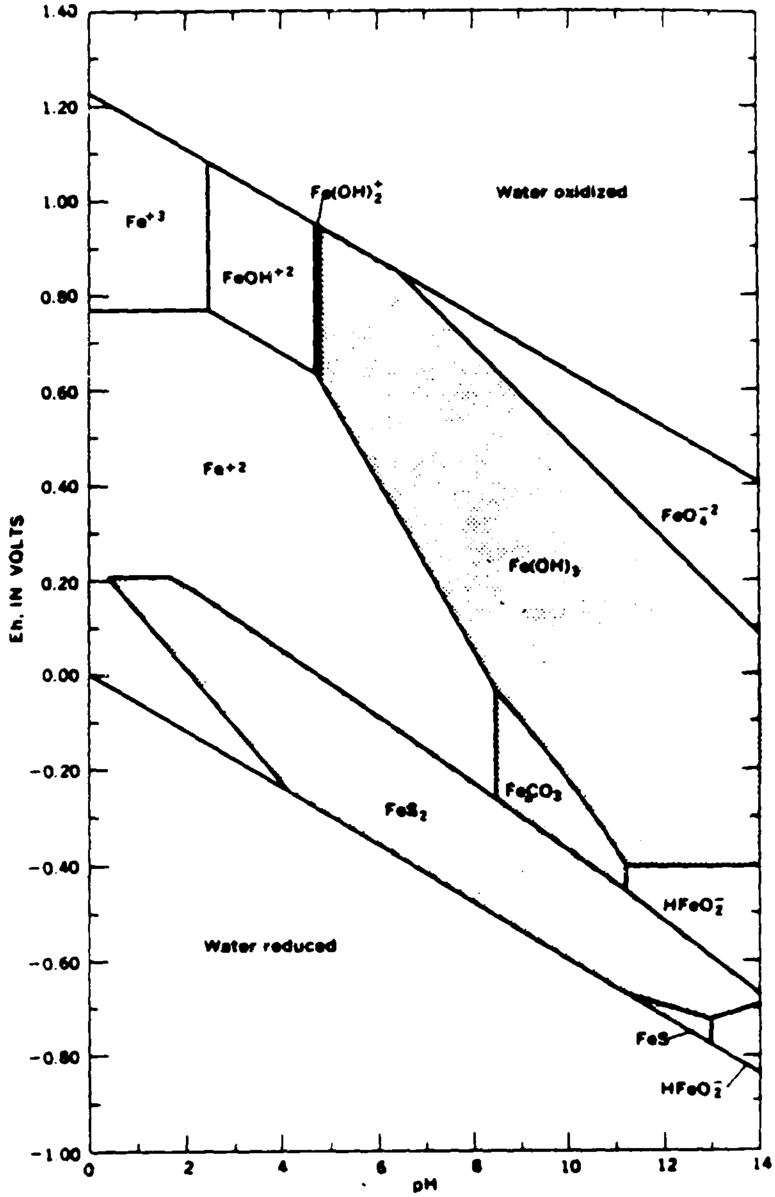

Figure 6. Fields of stability for solid and dissolved forms of iron as a function of Eh and pH at 25° C and 1 atmosphere of pressure. Activity of sulfur species 96 mg/ℓ as SO_4^{-2}, carbon dixoide species 1,000 mg/ℓ as HCO_3^- and dissolved iron 0.0056 mg/ℓ. (Hem 1970)

dissolved oxygen levels are depleted by contact with reduced iron minerals. Under such conditions, ground water can carry significant concentrations of ferrous iron in solution (Figure 6). However, where the ground water

encounters oxygenating conditions, which commonly occurs during pumping of a well, the ferrous iron will oxidize rapidly to the ferric iron form. This is evidenced where ground water is clear when first drawn from a well, but soon becomes cloudy and then brown from precipitating ferric hydroxide. Under such oxygenating conditions, the Eh value of the water is raised above 0.4 V and the solubility of iron is very low (Figure 6).

40. Investigation of the development of iron bacteria in ground water and wells have shown that these organisms characteristically occur within a defined Eh range. Hanert (1981a) reported that *Gallionella* occur most abundantly in nonorganic, iron-bearing waters characterized by a low redox potential in an Eh range of +200 to +320 mv. He also cited that the pH environmental limits for *Gallionella* range from 6.0 to 7.6 and that dissolved oxygen measurements show a range of 0.1 to 1.0 mg/ℓ. These Eh and pH limits characterize *Gallionella* as a gradient organism that develops neither under strongly oxidizing conditions nor in a highly reducing zone. Based on stability field diagrams for iron, the Eh and pH environmental ranges for *Gallionella* are within the zone where ferrous iron is stable (Figure 6). Hanert (1981a) argues that the stability of ferrous iron is the essential factor in the environmental conditions for *Gallionella*, and is much more important than temperature and dissolved oxygen values. Other observations of the water quality of *Gallionella* habitats include 5 to 25 mg/ℓ of ferrous iron, greater than 20 mg/ℓ of carbon dioxide, a chemical oxygen demand (COD) of less than 12 mg/ℓ and a temperature range of 8 to 16° C (Hanert 1981a).

41. Hasselbarth and Ludemann (1972) also reviewed the chemical nature of ground water where *Gallionella* and *Siderococcus* were implicated in well clogging problems. By comparing the chemical water quality between these wells and other control wells which had not experienced iron bacteria problems, they concluded that an Eh value greater than −10 mv ± 20 mv, was necessary for the mass development of these organisms. They also stated that the measured range of pH values for the infected wells was 6.5 to 7.6 and they used these values to calculate an index of "reductivity intensity" (rH), where:

$$rH = Eh \div 0.0992T + 2pH$$

where

Eh = oxidation-reduction potential referred to normal hydrogen electrode

T = absolute temperature in degrees Kelvin

According to this index, Hasselbarth and Ludemann (1972) concluded that ground water with a rH value greater than 14.5 ± 1 was necessary for iron bacteria growth. This value is in general agreement with the observations of Hanert (1981a) that rH values for *Gallionella* habitats vary from 19 to 21. Other water quality factors or conditions cited by Hasselbarth and Ludemann (1972) for mass iron bacteria growth included dissolved oxygen concentrations below 5 mg/ℓ, a minimum ferrous iron range of 0.2 to 0.5 mg/ℓ and an adequate velocity of flow which must markedly exceed normal ground-water movement.

42. In 1975, a state-wide survey was conducted in Alabama to determine the distribution and occurrence of iron bacteria in water wells. Valkenburg et al. (1975) reported that as a result of sampling 109 water wells, they found the widespread development of *Gallionella* and "*Spherotilus*-like" genera in Alabama wells. Based on their sampling program, they concluded that the environmental conditions most conducive to iron bacteria growth included shallower well depth (less than 400 ft), water temperatures of about 10° C, dissolved ferrous iron concentrations greater than 0.25 mg/ℓ, a pH range between 6 and 8, dissolved oxygen levels around 1.0 to 3.0 mg/ℓ, and a moderate to high conductance range of 300 to 700 μohm/cm.

43. The environmental conditions for the mass growth and development of members of the Sideroscapsaceae family have also been studies (Hanert 1981b). Observations of the growth of *Siderocapsa*, *Naumanniella*, and *Siderococcus* in lake environments have shown these organisms to be microaerophilic, developing in zonal water quality areas characterized by dissolved oxygen levels less than 1.0 mg/ℓ, an rH index less than 19, and a dissolved ferrous iron concentration between 1.0 and 2.0 mg/ℓ. Hanert (1981b) also noted that optimal growth of Siderocapsaceae seems to take place where environmental conditions change from a highly reduced situation to an oxidized condition, under near neutral pH values.

44. A summary listing of the various environmental conditions reported for the growth of iron bacteria is shown in Table 2. Based on the : values, iron bacteria genera can generally be described as occurring in iron-bearing water and soil with neutral pH conditions and relatively low redox potentials.

Table 2

Environmental Conditions Characterizing the Growth of Iron Bacteria

Parameter	Range	Organism	Reference
Redox potential (Eh)	+200 to +320 mv	*Gallionella*	Hanert (1981a)
	>-10 mv ± 20 mv	*Gallionella* and *Siderococcus*	Hasselbarth and Ludemann (1972)
pH	6.5 to 7.6	*Gallionella* and *Siderococcus*	Hasselbarth and Ludemann (1972)
	6.0 to 8.0	*Gallionella* and *Sphaerotilus*	Valkenburg et al. (1975)
	6.0 to 7.6	*Gallionella*	Hanert (1981a)
	6.0 to 8.7	*Siderocapsaceae*	Hanert (1981b)
	6.7 to 7.7	*Clonothrix*, *Crenothrix*, *Leptothrix*, and *Siderocapsa*	Rao (1970)
Reductivity intensity (rH)	>14.5 ± 1	*Gallionella* and *Siderococcus*	Hasselbarth and Ludemann (1972)
	19 to 21	*Gallionella*	Hanert (1981a)
	<19	*Siderocapsaceae*	Hanert (1981b)
Dissolved ferrous iron	5 to 25 mg/ℓ	*Gallionella*	Hanert (1981a)
	>0.2 to 0.5 mg/ℓ	*Gallionella* and *Siderococcus*	Hasselbarth and Ludemann (1972)
	>0.25 mg/ℓ	*Gallionella* and *Sphaerotilus*	Valkenburg et al. (1975)
	1.0 to 2.0 mg/ℓ	*Siderocapsaceae*	Hanert (1981b)
	0.2 to 5.0 mg/ℓ	*Clonothrix*, *Crenothrix*, *Leptothrix*, and *Siderocapsa*	Rao (1970)

(Continued)

Table 2 (Concluded)

Parameter	Range	Organism	Reference
Dissolved oxygen	0.1 to 1.0 mg/ℓ	*Gallionella*	Hanert (1981a)
	<5 mg/ℓ	*Gallionella* and *Siderococcus*	Hasselbarth and Ludemann (1972)
	1.0 to 3.0 mg/ℓ	*Gallionella* and *Sphaerotilus*	Valkenburg et al. (1975)
	<1.0 mg/ℓ	*Siderocapsaceae*	Hanert (1981b)
Chemical oxygen demand (COD)	<12 mg/ℓ	*Gallionella*	Hanert (1981a)
	>5 to 25 mg/ℓ	*Gallionella* and *Siderococcus*	Hasselbarth and Ludemann (1972)
Temperature	8 to 16° C	*Gallionella*	Hanert (1981a)
	10° C	*Gallionella* and *Sphaerotilus*	Valkenburg et al. (1975)
Carbon dioxide	>20 mg/ℓ	*Gallionella*	Hanert (1981a)

These organisms are predominantly microaerophilic and require limited organic material for growth, with the possible exception of chemoautotrophy in *Gallionella*. This typical environmental profile of iron bacteria growth conditions should be kept in mind when reviewing iron bacteria problems in ground water and wells. Where water quality analyses indicate alkaline pH, high redox potentials and oxygen rich waters, clogging problems from ferric hydrate precipitate may be simply attributed to chemical processes rather than to an iron bacteria infestation.

PART III: IRON BACTERIA RELATED PROBLEMS

Physical Clogging

45. Iron bacteria are predominantly regarded as fouling agents which result in physical clogging problems in underground drainage systems (Ford and Tucker 1975, Ford 1979), water supply systems (Starkey 1945), and wells (Rao 1970; Mogg 1972; Hasselbarth and Ludemann 1972). These organisms are responsible for significant clogging problems as a result of their ability to precipitate ferric iron as well as produce extracellular polysaccarides or similar "slime-like" organic polymers which encapsulate the sheaths and cell walls of these bacteria.

46. With regard to water wells, the accumulation of iron hydrates and extracellular bacterial slimes can clog well screens, gravel packs, pump intakes, pipelines, filters, and other water well system components. This plugging phenomena is manifested by inefficient well hydraulics, including reduced specific capacities and lower pumping levels. Iron bacteria clogging in wells is usually distinguished from chemical iron deposition problems by the rapid reduction of well flows, in which yields may decline as much as 75 percent in a year's time (Luthy 1964). Mogg (1972) presented records kept over a ten-year period for a well infested with *Gallionella* (Figure 7). These records show specific capacity reductions of greater than 50 percent in addition to the frequent need for well redevelopment.

47. Iron bacteria clogging problems in ground water and wells ultimately result in reduced life of well equipment, reduced well capacity, and redevelopment expense. Cullimore and McCann (1977) reported that iron bacteria problems in the southern half of Saskatchewan were responsible for four to six million dollars, annually, in well maintenance and rehabilitation costs. This reference serves to highlight the economic impact of iron bacteria problems in wells.

Bacteriologically Assisted Corrosion

48. An early misconception regarding iron bacteria was that these organisms directly attacked ferrous metal surfaces in water in order to utilize the iron during their growth. Later research, however, showed that iron

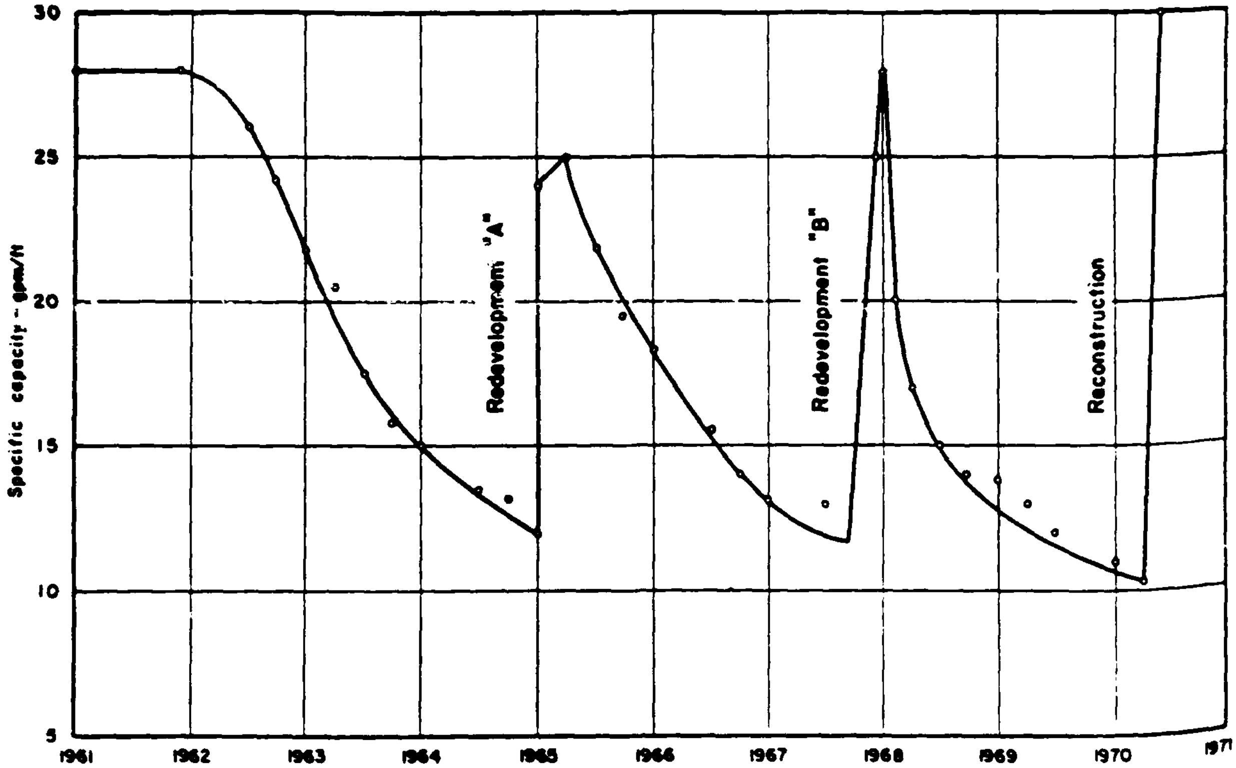

Figure 7. The effect of *Gallionella* clogging on the specific capacity of a well (Mogg 1972)

bacteria are capable of growing on nonferrous materials submerged in water, and that their nutritional iron requirements can be met by dissolved ferrous iron already in solution. Although iron bacteria are no longer viewed as direct agents of corrosion, Starkey (1945) introduced the theory that iron bacteria may aid certain electrolytic processes and may enhance the growth of other bacteria which are directly involved in metal corrosion.

49. Figure 8 depicts a typical electrolytic corrosion process involving anodic and cathodic areas on a metal surface. The anodes and cathodes represent regions with differing electrical charge and between which are established weak electrical potentials. In galvanic cells involving metals, corrosion always takes place at the anode where the metal is dissolved (oxidized) so as to form ions along with the release of electrons. The electrons pass through the metal to the cathode where they combine with hydrogen ions from the water to form atomic hydrogen (H). This deposition of cathodic hydrogen inhibits further corrosion reactions by reducing the electrical potential

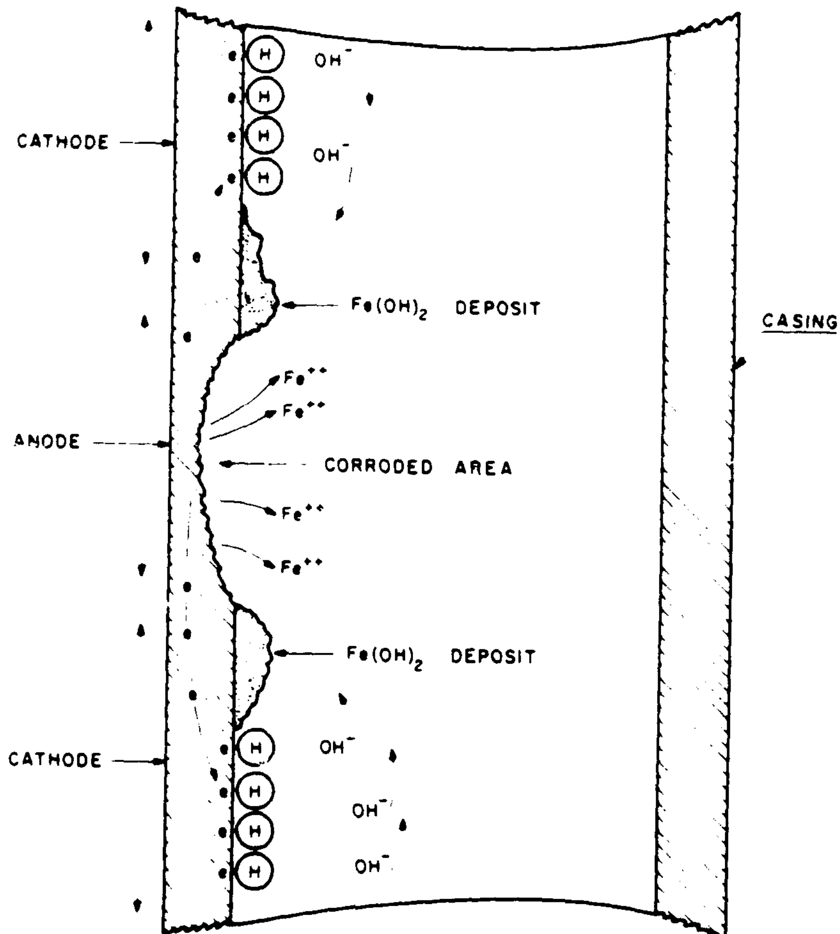

Figure 8. Typical electrolytic corrosion process (Clarke 1980)

between the anodic and cathodic areas (Clark 1980). In addition, where iron corrosion occurs, the dissolved ferrous iron from the anodic area will combine with hydroxyl ions in the surrounding water and deposit a low soluble compound, ferrous hydroxide (Figure 8). If oxygen is present in the water, this compound will be oxidized to ferric hydroxide which will collect on the metal surface. The ferric hydroxide, like cathodic hydrogen protects the metal surface from additional corrosion by reducing the electrical potential between the anode and cathode. Smith (1980) contended that iron bacteria can accelerate the corrosion process by utilizing the ferrous iron from corroding iron and precipitating ferric hydrates around their cells, as opposed to directly on the metal surface. By displacing the ferric hydroxide, the iron bacteria preserve the electrical potential between the anode and cathode and thus enhance corrosion.

50. Starkey (1945) proposed that the iron bacteria were associated with corrosion processes as a result of their extracellular slimes and ferric

hydrate deposits which would provide a suitable growth environment for sulfate-reducing bacteria. The sulfate-reducing bacteria are anaerobic and are capable of developing within anoxic zones between metal surfaces and the accumulated organic and iron hydrate products of iron bacteria (Starkey 1945). By reducing sulfates to sulfides, these bacteria obtain the necessary energy to oxidize organic material for cell growth. The resulting sulfides, however, combine with cathodic hydrogen to form hydrogen sulfide. Corrosion processes are therefore enhanced as the cathode is left unprotected and the electrical potential between the anodic and cathodic areas is maintained. In addition, hydrogen sulfide reacts with ferrous iron to form ferrous sulfide which is anodic to iron, and therefore a corrosive agent in and of itself (Figure 9). Smith (1980) further showed that these bacterial corrosion sites become tuberculated, being characterized by soft, raised features on badly corroded pipe. These tubercles perpetuate the galvanic corrosion process by providing a suitable environment for sulfate-reducing bacteria and by creating new electrical potentials between the anoxic interior of the tubercle and the surrounding water which contains dissolved oxygen (Figure 10).

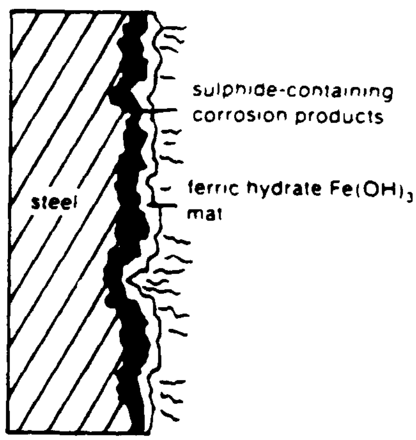

Figure 9. Diagram showing anoxic, corrosive sulfide zone beneath ferric hydrate and gelatinous deposits from iron bacteria (Smith 1980)

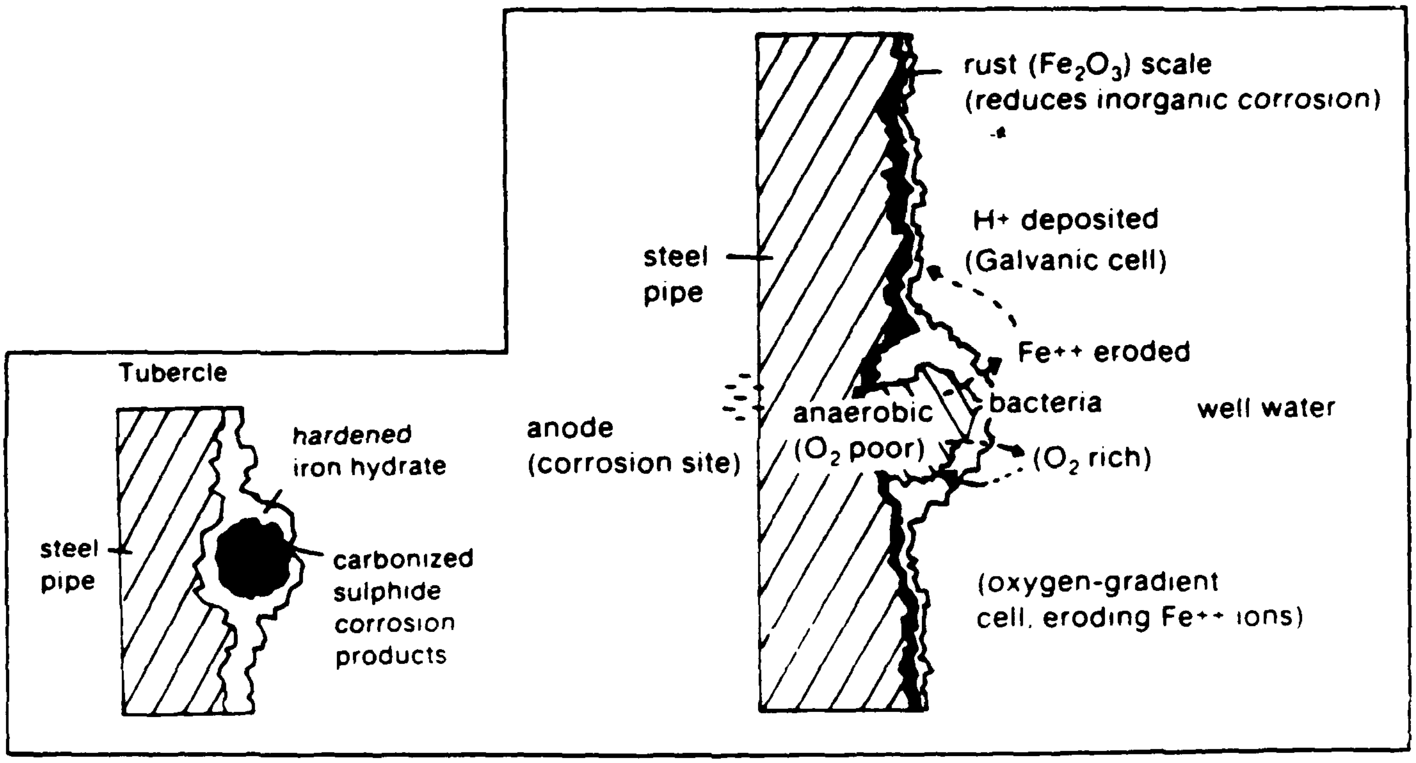

Figure 10. Diagram showing a tubercule and the mechanism in which these areas contribute to the metal corrosion process *(Smith 1980)*

PART IV: CONTROL OF IRON BACTERIA

Chemical Methods

51. Many chemical treatments have been suggested for the control of iron bacteria in ground water and wells including various disinfectants, copper salts, organic and inorganic acids, surfactants, and an array of proprietary products. Among these chemical agents, calcium and sodium hydrochlorite, hydrochloric (muriatic) acid and sulfamic acid are widely recommended and used for rehabilitating wells affected by iron bacteria (Stott 1973, Schafer 1974). The success of these and other chemical treatment methods, however, has been variable as exemplified by numerous reported incidences of recolonization or regrowth in the treated wells, sometimes within short periods of time (Mogg 1972, Cullimore and McCann 1977). In these instances, the chemical treatment must be repeated at regular intervals in order to control the growth of these organisms.

52. A number of reasons have been postulated as to why iron bacteria present such a challenge to chemical control methods. One reason is that the chemical agent may be ineffective or limited in its ability to penetrate the ferric hydrate deposits and extracellular organic slimes or sheaths which accumulate around the iron bacteria cells. In addition, ground-water temperatures are cold, resulting in reduced chemical activity. Concomitantly, iron bacterial are psychrophilic (growing best at colder temperature) and have a slower metabolic rate, resulting in less absorption of the chemical agent. Many chemical agents are also neutralized or inactivated by the presence of other organic or inorganic substances in the ground water, thereby depleting the concentration of the chemical below levels necessary for an effective bactericidal kill. Similarly, concentrations of the chemical agent may be diluted to ineffectual levels by ground-water hydraulics at the treated well site. Finally, the iron bacteria may be capable of growing outside the chemical treatment zone and may be later carried by ground-water flow back to the treated well.

53. Grainge and Lund (1969) noted that despite a continued proliferation of recommended chemical treatments for the control of iron bacteria in ground water and wells, many of these methods were found to be ineffective. They observed that although these chemical treatment strategies are directed

at the destruction of the iron bacteria themselves, the bactericidal effectiveness of many of these compounds had not been scientifically evaluated under controlled conditions. This lack of bactericidal data was attributed to the difficulties involved in culturing many of these organisms for study (Grainge and Lund 1969).

54. The lack of success of some chemical treatments, however, is due in part to inappropriate techniques employed by the user as opposed to deficiencies with the treatment process (Cullimore and McCann 1977). Descriptions of remedial treatment procedures are often anecdotal and the techniques used are sometimes based on empirical guesswork. To overcome this, more attention needs to be given to assessing and characterizing the degree of iron bacteria problems in wells to determine the necessary level of chemical treatments. Details regarding the chemical treatment process must include chemical concentrations, contact times, and chemical application methods which are sufficient to allow total penetration of the iron bacteria, by the chemical agent, in the well.

55. Chemical treatments for the control of iron bacteria in ground water and wells have typically employed the use of three categories of chemicals: (a) disinfectants; (b) acids; and (c) surfactants (Gass et al. 1983). These chemicals may serve as biocides and agents for dissolving or dispersing the ferric hydrate and organic slime deposits associated with iron bacteria growth. The chemical treatments may be used individually or used in an alternating series, such as acid treatment followed by disinfection.

Disinfectants

56. Chemical agents which are employed to directly destroy or inactivate the cells of iron bacteria are classified as disinfectants. Within the water well industry, chlorine is the most widely used disinfectant for treating iron bacteria problems in wells (Schafer 1974). Chlorine compounds have several advantages over other chemical disinfectants in that they are inexpensive, readily available and proven effective against a wide variety of bacteria.

57. The effectiveness of chlorine as a disinfectant is the result of the strong oxidizing nature of chlorine and its aqueous compounds. When chlorine gas is added to water, a mixture of hypochlorous (HOCl) and hydrochloric (HCl) acids is formed:

$$Cl_2 + H_2O \rightleftharpoons HOCl + H^+ + Cl^-$$

The formation of hypochlorous acid is important because this compound retains the oxidizing property of chlorine and it is in this form that the principal disinfecting action of chlorine occurs. It is generally thought that the death of bacterial cells results form hypochlorous acid oxidizing essential bacterial enzymes thereby disrupting the metabolism of the organism. In addition, hypochlorous acid has a small molecular size and is electrically neutral, thereby allowing rapid penetration through the bacterial cell wall (American Water Works Association 1973).

58. Hypochlorous acid in solution, however, ionized or dissociates into hydrogen and hypochlorite (OCL^-) ions; the degree of dissociation depends on water pH and temperature:

$$HOCl \rightleftharpoons H^+ + OCl^-$$

Where the pH of the water is below 6, the chlorine will exist predominantly in the hypochlorous acid form. Between a pH range of 6.0 and 8.5, however, hypochlorous acid rapidly dissociates into hypochlorite ion, and above a pH of 8.5, the hypochlorite ion is the predominant form of chlorine. This is important to the disinfection process because the hypochlorite ion is not as strong as oxidizing agent as hypochlorous acid and the negative charge of the ion impedes its ability to penetrate the organism's cell wall. Hence, the hypochlorite ion is not as effective a disinfection agent as hypochlorous acid. The pH of ground water is normally within the range where chlorine may exist as both hypochlorous acid and hypochlorite ion. Chlorine existing in water as hypochlorous acid and hypochlorite ions is defined as "free residual chlorine."

59. Chlorine-based compounds, such as calcium hypochlorite ($Ca(OCl_2)$, with 70 percent available chlorine) and sodium hypochlorite (NaOCl, typically with 5 to 12 percent available chlorine) are commonly used for treating wells with iron bacteria problems. These compounds ionize in water, similar to chlorine gas, and yield hypochlorite ions:

$$Ca(OCl)_2 + H_2O \rightleftharpoons Ca^{+2} + 2\ OCl^- + H_2O$$

$$NaOCl + H_2O \rightleftharpoons Na^+ + OCl^- + H_2O$$

These hypochlorite ions also combine with hydrogen to form hypochlorous acid, as shown in the previous equilibrium equation. Therefore, the same free residual chlorine in water is formed regardless of whether chlorine gas or hypochlorite chlorine compounds are used.

60. Along with an understanding of the term "free residual chlorine," the effective use of chlorination for the control of iron bacteria in ground water and wells requires an understanding of the terms "chlorine dosage," "chlorine demand," and "contact time." The total amount of chlorine added to water, usually measured in either parts per million or milligrams per liter is referred to as the chlorine dosage. However, as quickly as chlorine is added to water, a portion of the chlorine dosage will be lost as the chlorine oxidizes both organic matter and reduced inorganic minerals. These organic and inorganic compounds which react with and neutralize chlorine in water are said to exert a chlorine demand. If the chlorine dosage to a water supply is equal to the chlorine demand, no free residual chlorine will be formed, resulting in no disinfection action. Therefore, when chlorinating a well for the treatment of iron bacteria problems, the chlorine dosage must exceed the chlorine demand exerted by extraneous organic and inorganic materials in the ground water in order to produce a free residual chlorine which will have a bactericidal effect on the iron bacteria. In addition, the concentration of free residual chlorine formed during the treatment process will determine the amount of time the chlorine must be in contact with the iron bacteria in order to achieve an adequate bactericidal kill. This length of exposure of the targeted bacteria to the free chlorine residual is termed contact time.

61. Although the technology for chlorinating wells clogged by iron bacteria has existed since the early 1900's (White 1972), Grange and Lund (1969) were the first researchers to demonstrate, under controlled laboratory conditions, the bactericidal effectiveness of chlorine against iron bacteria. They reported that free chlorine residuals between 300 and 500 mg/ℓ over an 18 hr contact time effectively killed iron bacteria. In addition, they noted that a lower free residual chlorine concentration of 25 mg/ℓ, a minimum contact time of 24 hr would be required to dislodge filamentous iron bacteria deposits from the walls of wells.

62. The results of the study by Grainge and Lund (1969), coupled with empirical observations made over the years, has resulted in a set of generally recognized procedures for chlorinating wells with iron bacteria problems (Johnson Division 1972, White 1972). This procedure involves the use of either calcium hypochlorite or sodium hypochlorite in order to provide a chlorine dosage which will result in a 200 to 500 mg/ℓ free residual of chlorine in the well water. After introducing the chlorine into the well, the chlorinated water is forced out into the water-bearing formation by one of several physical surging techniques, including air lifting or the use of a mechanical surge block (Gass et al. 1983). The surging action not only forces the chlorinated water out into the formation, but also physically agitates the ferric hydrate and organic slime deposits so as to break up these deposits. This action results in a more thorough contact between the iron bacteria and the chlorine residual. A contact time of 24 hr is usually prescribed, during which time the well is periodically surged and the free residual chlorine concentration checked. If the free residual chlorine concentration falls below the necessary level for an effective bactericidal kill, the chlorine dosage is increased. After 24 hr, the well is pumped free of chlorinated water and normal well operations resumed. In some instances, three or four successive chlorine treatments are performed to increase the likelihood that the chlorinated water is flushed out into the formation around the well (Johnson Division 1972).

63. Under controlled laboratory conditions, Valkenburg et al. (1975) investigated the bactericidal effectiveness of selected chlorine and quaternary ammonium compounds on iron bacteria. Using *Gallionella* cultures, they demonstrated that two quaternary ammonium compounds, Bardac-11™ and benzethonium chloride, were effective in destroying *Gallionella* at low concentrations. Figure 11 shows a 50 mg/ℓ of Bardac-22™ and 300 mg/ℓ of benzethonium chloride were reported to have killed *Gallionella* after a 3 hr exposure at 20° C. The active bactericidal ingredient in quanternary ammonium compounds is n-alkyl dimethyl benzyl ammonium chloride which, in addition to being a strong disinfectant, possesses cleaning (detergent) properties due to its surfactant activity. Valkenburg et al. (1975) postulated that the successful destruction of *Gallionella* by the quaternary ammonium compounds was due to the detergent action of these disinfectants and the resulting ability of the compound to penetrate ferric hydrate deposits around the organisms. In the same

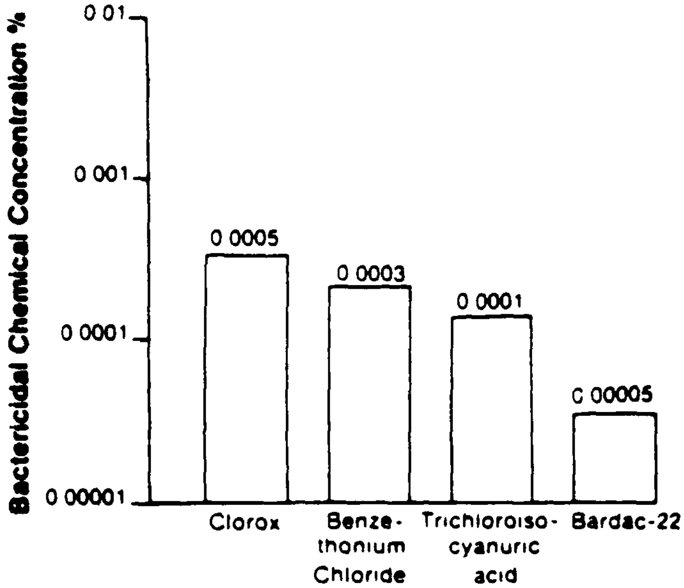

Figure 11. Bactericidal chemical concentrations necessary to kill *Gallionella* organisms after 3 hr of exposure at 20° C (Valkenburg et al. 1975)

study, Valkenburg et al. (1975) also demonstrated the bactericidal effectiveness of chlorine against *Gallionella* by using Clorix™, which is a sodium hypochlorite solution with 5.25 percent available chlorine, and trichloroisocyanuric acid, which is an organic chlorine compound with 90 percent available chloride (see Figure 11). Despite these laboratory findings, Valkenburg et al. (1975) concluded that future field experimentation was necessary to fully assess the long-term effectiveness of all these disinfectants against iron bacteria populations in wells.

64. Cullimore and McCann (1977) also examined the ability of several different disinfectants to inhibit the growth of *Gallionella* and *Crenothrix* cultures. They demonstrated that the effectiveness of most disinfectants differed significantly with the number of cells present in each 15 mℓ culture (Table 3). For example, Javex™, which is a sodium hypochlorite solution containing 5.5 percent available chlorine, prevented the growth of iron bacteria at a free chlorine residual concentration of 250 mg/ℓ, where the density of bacteria cells was less than 100/15 mℓ. However, where the density of bacteria cells was 700,000 to 1,000,000 cells per 15 mℓ, the concentration of chlorine residual required to prevent bacterial growth was 10,000 mg/ℓ. Cullimore and McCann (1977) concluded that the selection of a disinfectant

Table 3

Extrapolated Effective Control Concentration (mg/ℓ) for Five Disinfectants Against A Range of Cell Concentrations of Iron Bacteria (Cullimore and McCann 1977)

Disinfectant*	Cell Concentration of Iron Bacteria (cells per 15 mℓ) 30** to 100	300 to 1,000	3,000** to 10,000	70,000 to 100,000	700,000** to 1,000,000
Javex† (sodium hypochlorite, 5.5 percent available chlorine)	250	750	850	1,000	10,000
HTH† (Calcium hypochlorite, 70 percent available chlorine)	2,000	5,000	7,500	10,000	100,000
IP (iodine polymer)	10	20	30	40	NC
$CuSO_4$	500	1,000	5,000	50,000	10,000
$KMnO_4$	10-20	100	250	500	5,000

* All data for pH of 7.4.
** Based on hypochlorite concentration.
† Extrapolated data.
NC = No control since the solubility of IP in water is very low.
ND = Not determinable from data.

concentration for the control of iron bacteria in wells must reflect the density of cells within the proposed treatment area.

65. Cullimore (1979a) also conducted a series of laboratory trials to determine the relative effectiveness of different chemical disinfectants against strains of *Gallionella*, *Crenothrix*, and *Sphaerotilus* iron bacteria. The results of these trials are shown in Table 4. Cullimore (1979a) showed that two chlorine compounds, chlorine dioxide and hypochlorites, were more effective than the other compounds based on an "assimilated rating." This rating involved averaging the effectiveness of a particular chemical to kill the iron bacteria over a concentration range which varied from 100 to 10,000 mg/ℓ over a maximum contact time of 6 days. In addition to chlorine, quanternary ammonium compounds were also shown to be generally effective against the iron bacteria. Cullimore (1979a), however, cautioned that the laboratory findings may not be indicative of actual field results because the laboratory trials were conducted with the iron bacteria in suspension, so that

Table 4

Relative Effectiveness of Selected Disinfectants Against *Gallionella*, *Cronethrix*, and *Sphaerotilus* (Cullimore 1979a)

Compound	Assimilated Rating*	Code**
Chlorine dioxide	82	Cl
Hypochlorite	74	Cl
San Q-5	69	QAC
Hyamine	68	QAC
QA	64	Form
Triton X100	39	S
Iodine	33	I
Rexol	30	S

* Rating of the chemical to kill iron bacteria over a concentration range from 100 to 10,000 mg/ℓ over a maximum 6 day contact time.

** Active component; Cl = chlorine; QAC = quaternary ammonium compound; Form = a special formulation of quaternary ammonium compound, surfactant, iodine, citric acid, and inorganic salt nutrients; S = surfactant; I = iodine.

the disinfectant was readily able to penetrate small groups of cells. These trials, therefore, did not evaluate the relative effectiveness of these disinfectants against an iron bacterial slime growth on a fixed surface. Cullimore (1979a) concluded that field evaluations of chlorine and quaternary ammonium compounds were needed to determine the bactericidal effectiveness of these compounds when applied to actual iron bacterial infestations in ground water and wells.

Acids

66. Acids are another category of chemicals which may be used for rehabilitating wells clogged by iron bacteria. The main value of acids is the ability to chemically dissolve the ferric hydrate deposits which accumulate around these organisms. In addition, some acids in high concentrations may serve as disinfectants and may also help to disperse and loosen the extracellular slime material deposited by the iron bacteria (Mogg 1972). Valkenburg et al. (1975) showed that a concentration of 4,000 mg/ℓ of acetic acid and

7,300 mg/ℓ of hydrochloric acid were capable of inhibiting *Gallionella* growth under laboratory conditions (Figure 12). Luthy (1964) and Cullimore and McCann (1977) also reported that a proprietary organic acid, LBA™ (liquid antibacteria acid), was effective in controlling the growth of iron bacteria when used at a manufacturer's recommended concentration of 5 percent (50,000 mg/ℓ) over a 36 hr contact time.

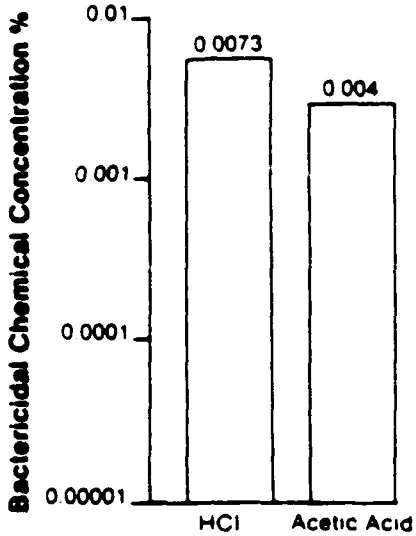

Figure 12. Lowest concentration of acids that will kill *Gallionella* organisms after 3 hr of exposure at 20° C (Valkenburg et al. 1975)

67. The acids most commonly used as chemical treatments for the control of iron bacteria in wells include hydrochloric acid (HCL) and sulfamic acid (NH_2SO_3H) (Schafer 1974, Cullimore and McCann 1977). Hydrochloric (muriatic) acid is commercially prepared as a solution and is available in several strengths, the most common being 28 percent This acid may also be sold with an inhibiting agent, such as a gelatin-based compound, which serves to lessen the tendency of the acid to attack and corrode metal surfaces during the well treatment process. Sulfamic acid is available as a dry, granular material and forms a strong acid when dissolved in water. The solubility of sulfamic acid in water increases with temperature, ranging from 15 to 20 percent by weight at most ground-water temperatures (Johnson Division 1972). Sulfamic acid reportedly is a slower-acting acid than hydrochloric acid and therefore has a less corrosive effect on metal well components.

68. Similar to disinfectants, the concentration and contact times for hydrochloric and sulfamic acids, when used to treat iron bacteria problems in wells, should vary depending on the density of the organisms in the treatment zone. Table 5 contains one proposed scheme recommended by Cullimore and McCann (1977). As can be seen from Table 5, the necessary acid concentrations may vary from 7.5 to 21 percent and recommended contact times may range from 6 to 24 hr.

Table 5

Potential Acid Treatments Listing Time-Chemical Concentrations For the Control of Iron Bacteria (Cullimore and McCann 1977)

Density of Iron Bacteria		Chemical Treatment: Hydrochloric Acid	Chemical Treatment: Sulfamic Acid
1 to 300 cells/mℓ	Concentration (percent)	14	7.5
	Time (hr)	6	12
300 to 5,000 cells/mℓ	Concentration (percent)	18	10
	Time (hr)	12	24
5,000 to 50,000 cells/mℓ	Concentration (percent)	21	10
	Time (hr)	24	48

69. In addition, the method used to apply the acid to a well during treatment for iron bacteria is important. Because these acids are heavier than water, the acid should be introduced to the proposed treatment zone by pouring the solution down a conductor pipe. This allows the concentrated acid to be initially emplaced in the areas of the well which require direct treatment. Once in the well, however, the acid solution should be agitated so that a uniform mixture is achieved throughout the treatment zone. As with disinfectants, agitation can be accomplished with a jetting tool, surge block, or compressed air in order to force the acid out into the formation and to break up the ferric hydrate and bacterial slime deposits.

70. Most chemical treatment strategies for controlling iron bacteria in ground water and wells use a series of separate treatments involving acid followed by a disinfectant. This strategy recognizes the primary capability of acid to dissolve encrusted deposits of ferric hydrates and to loosen iron bacteria slimes. Once the spent acid is removed from the treated well, a disinfectant is used to achieve the desired bactericidal kill. This treatment

series may be repeated several times in order to effectively remove all the iron bacteria deposits and suppress the growth of these organisms.

Surfactants

71. Surfactants are another category of chemicals which may be used, especially in conjunction with disinfectants, for treating wells with iron bacteria problems. These chemicals have a detergent capability in which they attach onto ionic particles, such as clays, colloids, and metal ions, forming large complex particles with the same electrical charge. Because similar electrically charged particles tend to repel each other, these particles are broken up and dispersed. Chemicals which can create these uniform charged particle complexes are referred to as "surface-active agents" or surfactants.

72. Within the water well industry, glassy sodium phosphates (polyphosphates) are useful in the treatment of wells with iron bacteria problems because they can effectively disperse the ferric hydrate deposits surrounding these organisms. Polyphosphates are typically applied at concentrations of approximately 3 percent (Gass et al. 1972). In addition a minimum 50 mg/ℓ free chlorine residual is always applied along with the polyphosphate in order to suppress the growth of bacteria which may utilize the polyphosphates as a nutrient source. A chemical treatment strategy for the control of iron bacteria in wells might therefore utilize polyphosphates as a pretreatment to disinfection or may use polyphosphates concurrently with a compatible disinfectant in order to promote a more effective penetration of the iron bacteria by a bacteriocide. Cullimore (1979a) also showed that surfactants did kill some iron bacteria in laboratory studies, presumably due to the dispersion of the protective slime coating which forms around the cell (Table 4).

73. Regarding the method of application, polyphosphates are dissolved slowing in a mixing tank and introduced into the well as a solution. As with all other chemical treatments, once the polyphosphates are placed in the well, vigorous mechanical agitation, such as surging or jetting, is employed to enhance loosening and dispersion of the ferric hydrate deposits. Two or more successive treatments of polyphosphates are usually performed in order to increase the likelihood that the chemical solution will be forced out into the surrounding formation.

Physical Methods

74. In contrast to chemical methods, physical treatment methods for controlling iron bacteria in ground water and wells has only received attention within the last 10 years. Much of this attention has been brought about by researchers attempting to find alternatives to traditional chemical treatment strategies which may not have produced desired rehabilitation results. Unlike the traditional chemical treatment strategies for iron bacteria in wells, physical control methods have centered on the destruction of the organisms themselves and on the alteration of ground water and well environments so as to manipulate the growth of these bacteria. The more prominent physical control methods investigated to date include: (a) ultraviolet light; (b) ultrasonic vibration; (c) heat treatment (pasteurization); and (d) changing the redox potential of ground water.

Ultraviolet light

75. Ultraviolet light has been known to be an effective physical bactericidal disinfectant since the 1940's (National Academy of Sciences 1980). The mechanism of disinfection action is believed to be the denaturation of essential nucleoproteins, which results from the direct absorption of ultraviolet energy by the organism. For disinfection purposes, ultraviolet lamps are designed to provide a maximum amount of light at the proper wavelength (2,537 Å units) for the greatest bactericidal action. In order for an ultraviolet disinfection unit to be effective, however, the water must be circulated to expose a maximum surface area of the bacteria to the ultraviolet light. Turbid water will significantly decrease the bactericidal effectiveness of ultraviolet light as a result of bacteria being "shadowed" by particulate matter, thereby preventing the killing rays of ultraviolet light from reaching the targeted organisms (Lehr et al. 1980).

76. Cullimore (1981a) conducted preliminary investigations into the use of "in-well" ultraviolet lamps to directly irradiate selective areas of a well which were subject to iron bacteria clogging. He concluded, however, that these bacteria were less sensitive to this treatment method because the organisms were shielded from the ultraviolet light by encrusted ferric hydrate deposits and extracellular polysaccharide slimes. As a result of these deposits and the turbid conditions which may occur within the well, Cullimore

(1981a) contended that ultraviolet light cannot be considered an effective treatment method for controlling iron bacteria infestations in wells.

Ultrasonic vibration

77. Cullimore and McCann (1977) discussed their investigation of ultrasonic vibration (sonication) as a possible physical treatment method for controlling the growth of iron bacteria in wells. Sonication involves utilizing the energy produced by sound waves so as to disintegrate individual bacterial cells. The ultrasound is generated by a probe which could conceivably be installed permanently or be periodically lowered into a well for treatment. Cullimore and McCann (1977) theorized that the ultrasonic probe in the well cold be used to remove the ferric hydrate and organic slimes deposited by the iron bacteria and to disintegrate the individual cells. They reported, however, that a series of experiments on *Gallionella* and *Crenothrix* showed that no significant reduction in the number of cells occurred, even after 60 min exposure time in a ultrasonic tissue dismembranator operating at 800,000 cycles/sec. Cullimore (1981a) later noted that there was even some evidence of reproduction occurring in the cultures. Cullimore and McCann (1977) credited this atypical survival capability of the iron bacteria to the extracellular gelatinous cell coatings which serve to lessen the effects of sonication. As a result, they concluded that conication would not represent an effective physical treatment method for controlling iron bacteria in wells.

Pasteurization

78. Pasteurization involves the application of heat to destroy microorganisms. Although the bactericidal effects of heat have been known since the 1860's when Louis Pasteur demonstrated that a temperature of 60° C for 30 min could kill spoilage bacteria, pasteurization is a relatively new approach to disinfecting water supplies. With regard to controlling iron bacteria in ground water and wells, preliminary studies have demonstrated that these organisms are heat sensitive and that growth in wells can be controlled by repeated heat treatments.

79. Valkenburg et al. (1975) first reported the sensitivity of *Gallionella* to heat. They demonstrated under laboratory conditions that 48° C was bactericidal to *Gallionella* following a 10 min exposure. Valkenburg et al. (1975) concluded that pasteurization may be of potential use in treating water wells contaminated with iron bacteria.

80. In addition, extensive laboratory and field studies conducted throughout the 1970s by researchers at the Regina Water Research Institute, University of Regina in Saskatchewan have shown that iron bacteria, as a group, are very sensitive to the elevation of water temperatures (Cullimore 1979b). Figure 13 depicts the influence of temperature on the growth of iron bacteria. As previously noted in this report, iron bacteria are psychrophilic and have an optimum growth temperature at approximately 10° C. When water temperatures are elevated to temperatures ranging from 32° to 45° C, however, the organisms cease to grow and their bacterial slimes are dispersed. As the water temperature raises above 54° C, the iron bacterial cells are rapidly killed. In practice, therefore, the use of steam or hot water to elevate ground-water temperatures above 54° C for a prescribed period of time, should represent an effective method for controlling iron bacteria growth in wells.

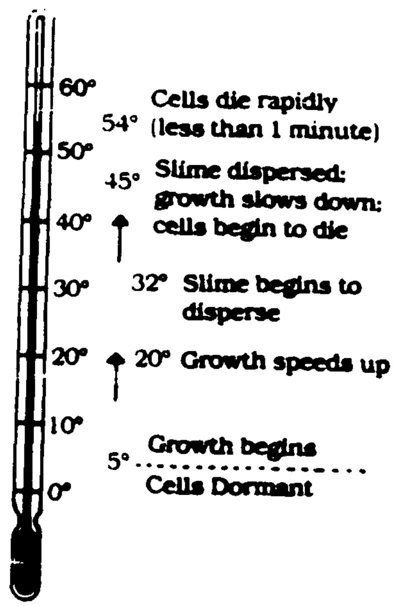

Figure 13. Effect of temperature on iron bacteria (Smith 1982)

81. Cullimore and McCann (1977) reviewed the findings of initial pasteurization field tests which were conducted on two wells near Regina, Saskatchewan using high-pressure steam injection. In both instances, the water temperature was raised to 65° C for 40 min and this treatment resulted in the dispersion of encrusted slime deposits and the killing of bacterial cells. Although these heat treatments were initially effective in restoring

well yields, the recurrence of iron bacteria populations after treatment was noted for both wells. Cullimore and McCann (1977) postulated that this recurrence of iron bacteria populations was the result of organisms surviving in the aquifer outside the treated zone, recolonizing the well after the pasteurization treatment. They concluded, therefore, that the control of iron bacteria problems would require regular pasteurization treatments of the wells.

82. Cullimore (1979b) also reported on a recycling hot water pasteurization system which was installed in a well at Bulyea, Saskatchewan. This field test demonstrated that the pasteurization temperatures had to reach a minimum of 38° C to cause dispersion of the iron bacterial slimes and 54° C to kill 99 percent of the cells in the treated volume of water. Although Cullimore (1979b) concluded that the pasteurization process was successful in restoring the yield of this iron bacteria clogged well, he acknowledged that the system had energy-efficiency problems. Most of the energy (between 60 and 81 percent) was lost by radiation of heat through the insulated pipes and also from the free discharge of hot water back down the well. In addition, recurring iron bacteria growth in the well resulted in a recommendation that the pasteurization treatment be repeated a minimum of once every three months. Cullimore (1981b) indicated that alternative energy-efficient and reliable portable or permanent heater systems were needed.

Changing the redox potential

83. Another physical treatment strategy which can be used to control iron bacteria problems in wells is to alter the redox potential of the ground water. As was earlier discussed in this report, redox is a measure of the oxidation or reduction potential occurring in water. Where dissolved oxygen is readily available in water, the redox potential (Eh) will be high and metals, such as iron and manganese, will be oxidized and precipitated from solution. In oxygen-deficient ground water, the Eh values will be low and the solubility of these metals will be high. With regard to iron bacteria occurrence in ground water, these organisms have been shown to favor relatively low redox potentials (between -10 mv and +350 mv) where they can compete with limited amounts of oxygen for the oxidation and deposition of iron. As a result, processes which influence the redox potential of ground water may be used to manipulate the growth of these organisms in aquifers and in wells.

84. One technique which attempts to selectively alter the redox potential of ground water not only for the removal of iron and manganese but also

for the control of iron bacteria is known as the Vyredox™ method. This system was first developed in Finland in 1955 and is a patented process (Zienkiewicz 1985). The Vyredox™ method actually makes use of existing iron precipitating bacteria in the ground water to control iron-related problems in a production well. This is done by using aeration wells to enhance bacterial growth in an area removed from the production wells. In this process, a percentage of water pumped from a producing water well is degassed, then aerated and returned to the aquifer through several small injection wells surrounding the producing well (Figure 14). This oxygenated water creates a zone, away from the producing well, favorable to both iron bacteria growth and the precipitation of iron and manganese oxides. As a result, dissolved iron and manganese in the ground water moving through the zone of elevated Eh is precipitated out of solution both chemically and biologically. Ground water recharging the producing well will therefore be low in iron and manganese concentrations and will be free of iron bacteria.

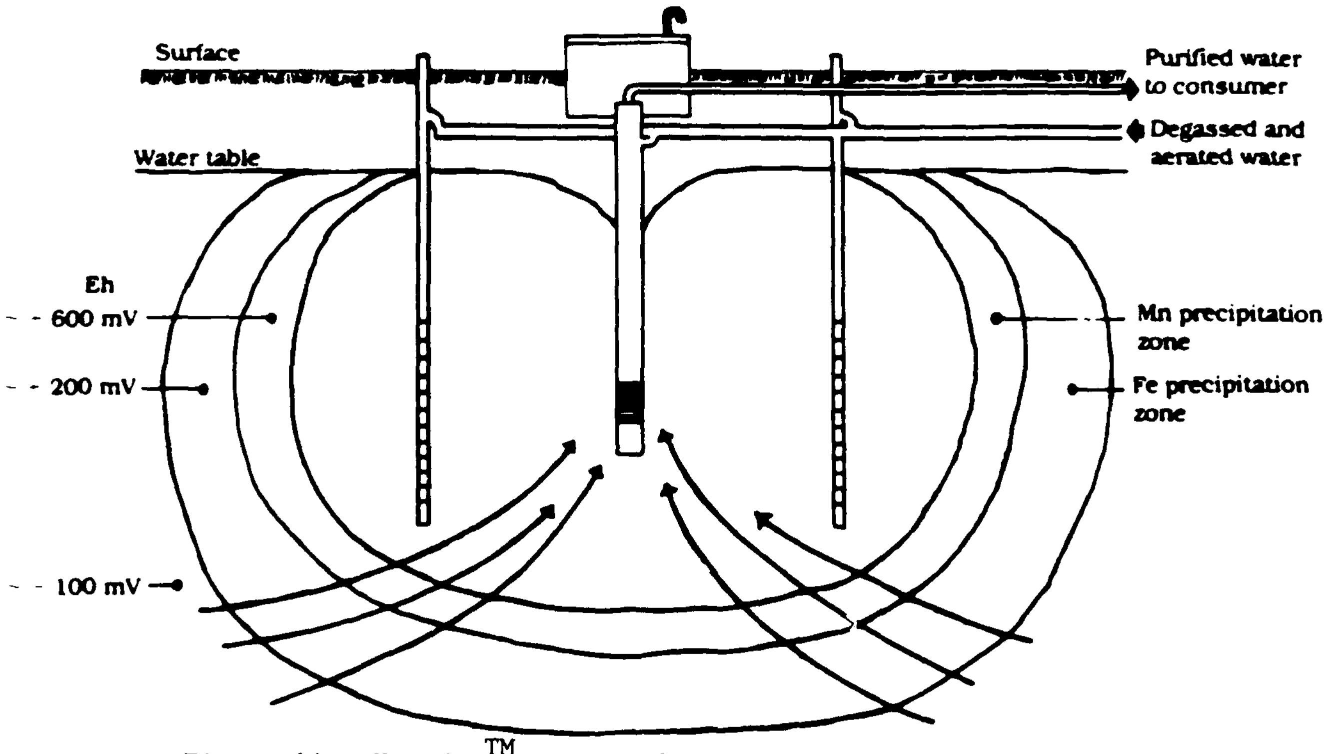

Figure 14. Vyredox™ method showing an iron and manganese precipitation zone which is created in the aquifer (after Zienkiewicz 1985)

85. The percentage of water from the production well which is aerated and returned to the aquifer may vary from a minimum of 4 percent to as high as 33 percent, depending on the hydrology of the site and the desired degree of water treatment (Zienkiewicz 1985, Cullimore 1981a). The size and dimensions of the recharge zone are determined from pilot studies and geological investigations of each proposed treatment site. The recharge zone must be large enough to allow adequate contact time for the precipitation of iron and manganese and must have an adequate porosity for the accumulation of these deposits (Zienkiewicz 1985). According to Armstrong (1978), the Vyredox™ method is primarily applicable to shallow sand and gravel aquifers (less than 300 ft).

86. Long-term blockage of the production well as a result of accumulated iron and manganese oxides and iron bacteria growth in the surrounding aquifer has led some researchers to question the Vyredox™ process. Hallberg and Martinell (1976), however, argued that such deposits would take hundreds of years to significantly reduce the yield of the production well. Since this process has only been in use in the United States since 1979, adequate time has not lapsed to document the validity of either view point. Consideration of capital costs, pumping costs and system maintenance, however, have limited the application of this process to commercial and municipal well use. Additionally, Cullimore (1981a) stated that an extensive cost/benefit study should be performed when considering the use of this procedure for controlling iron bacteria in wells.

PART V: CONCLUSIONS

87. "Iron bacteria" is a general term which refers to a wide variety of organisms which are quite diverse in morphology, physiology, and environmental occurrence. As a result of their ability to deposit ferric hydrate around their cells and to excrete extracellular polysaccharide slimes, these organisms are capable of causing significant clogging problems in ground water and wells, water-distribution systems and underground drainage systems. Additionally, iron bacteria are involved in bacteriologically assisted corrosion processes due to the incidental harborage of sulfate-reducing bacteria in their ferric hydrate and organic slime deposits. Iron bacteria problems in ground water and wells are recognized worldwide and may be locally responsible for multimillion dollar annual well maintenance and rehabilitation costs.

88. Despite the widespread familiarity with iron bacteria problems in wells, these organisms have not been the subject of systematic study. One reason for the lack of active microbial research on iron bacteria is that these organisms are difficult to culture for experimental study, and pure cultures of many of these organisms have never been obtained. As a result, much of the knowledge regarding the growth requirements of iron bacteria is rudimentary and an understanding of the environmental conditions necessary for their development is limited.

89. The lack of definitive information on the physiology and ecology of iron bacteria has hampered the development of effective treatment strategies for controlling the growth of these organisms in ground water wells. Remedial methods used to control iron bacteria in wells are frequently based on colloquial observations and the techniques used are often lacking scientific documentation. As a result, the success of many recommended iron bacteria treatment strategies has been variable, and recolonization or regrowth in the treated well is common.

90. Studies have demonstrated that selected chemicals are capable of effectively killing iron bacteria under laboratory conditions. Among these chemicals, chlorine and quaternary ammonium compounds have been shown to be the most effect disinfectants. The use of these and other chemicals for controlling iron bacteria populations in wells, however, requires systematic field evaluation in order to define the chemical concentrations, contact

times, and chemical application methods which will effectively remove actual iron bacteria infestations in wells.

91. Physical methods for controlling iron bacteria in ground water and wells, including heat treatment and the alteration of the ground water redox potential, have also been shown to be effective in pilot studies. Neither treatment process, however, has been commercially developed for small-scale use. Energy efficient and reliable equipment associated with the heat treatment of wells for iron bacteria control is not yet commercially available. In addition, the Vyredox™ method of altering ground-water redox potential, while proven effective in pilot and full scale installations, is a proprietary process and involves capital and operational maintenance costs which typically limit this method to municipal or commercial uses.

PART VI: RECOMMENDATIONS

92. Iron bacteria infestations in water wells are regarded as the most prevalent cause of bacterial degradation of well performance due to their ability to clog well intakes and surrounding aquifer materials with their characteristic deposits of ferric hydrate and gelatinous slime. Despite this well recognized problem, effective treatment strategies have been slow to develop as a result of what little is known about the physiology and ecology of this diverse group of organisms. In order to develop an effective treatment strategy for the control of iron bacteria problems in wells, further study is needed in the following areas:

a. Techniques for culturing and isolating iron bacteria need to be refined in order that these organisms be available for physiological and environmental control studies. These studies could generate additional knowledge about the specific growth requirements of various iron bacteria genera and identify key environmental conditions for their occurrence in ground water.

b. Additional field studies are needed to characterize the nature of iron bacteria populations in wells and to determine whether these organisms are indigenous to shallow water table aquifers. These studies should attempt to relate the occurrence and mass development of these bacteria to "indicator" ground water quality parameters such as redox potential, pH, dissolved oxygen, ferrous iron, total organic carbon, and temperature.

c. Continued research on techniques or methods for sampling and enumerating iron bacteria in aquifer materials is required. This research is needed to quantifiably assess the ability of these organisms to migrate with ground-water flow out into the aquifer away from an infected well.

d. Systematic field evaluations of some of the more promising disinfectants, including chlorine and quaternary ammonium compounds, are needed in order to determine the effectiveness of these compounds when applied to actual iron bacterial infestations in ground water and wells. Closer attention needs to be paid to the details of the chemical treatment process, including chemical concentrations, contact time, and chemical application methods. The degree of success of these treatments should be quantified by the enumeration of bacterial cells before and after treatment.

e. Field evaluations are needed to assess the effectiveness of a combination of chemical treatment processes used in successive series, such as the use of acids or polyphosphates prior to disinfection. Such processes may assist the disinfectant in reaching and contacting the iron bacteria cells located beneath the heavier layers of ferric hydrate deposits and organic slimes.

f. A field demonstration project utilizing an in-well immersion heater to pasteurize iron bacteria clogged wells is needed to determine whether such a process would be energy-efficient and suitable for development as a reliable portable, or permanently installed, heat treatment unit.

g. Additional methods or concepts for alternating ground-water redox potentials, such as anoxic blocks in a well, require research as a basis for controlling the growth of iron bacteria in wells. By creating redox conditions favorable for the growth of these organisms in wells, clogging may be prevented.

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